Arnold Schwarzenegger
Governor

PERFORMANCE, COST, AND ENVIRONMENTAL EFFECTS OF SALTWATER COOLING TOWERS

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
John S. Maulbetsch, Consultant
Michael N. DiFilippo, Consultant

January 2010
CEC-500-2008-043

Prepared By:

John S. Maulbetsch, Consultant
Menlo Park, CA 94025
Michael N. DiFilippo, Consultant
Berkeley, CA 94705

Commission Contract No. 500-02-014
Commission Work Authorization No: E2I-104

Prepared For:

Public Interest Energy Research (PIER) Program
California Energy Commission

Joe O'Hagan
Contract Manager

Linda Spiegel
Program Area Lead
Energy-Related Environmental Research

Kennneth Koyama
Office Manager
Energy Generation Research

Thom Kelly, Ph.D.
Deputy Director
ENERGY RESEARCH & DEVELOPMENT

Melissa Jones
Executive Director

Acknowledgments

The authors wish especially to acknowledge the time spent and the information provided by the staffs of St. Johns River Power Park, Plant Lansing Smith, Plant Crist, Plant Watson, the Pittsburg Power Plant, the Palo Verde Nuclear Power Station and GEA Integrated Cooling Technologies.

Please cite this report as follows:

Maulbetsch, John S., and Michael N. DiFilippo. 2008. *Performance, Cost, and Environmental Effects of Saltwater Cooling Towers.* California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2008-043.

Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts focus on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Performance, Cost, and Environmental Effects of Saltwater Cooling Towers is the final report for the Alternative Cooling Strategies and Technologies project (contract number CEC-500-2008-043, work authorization number E2I-104) conducted by John S. Maulbetsch and Michael N. DiFilippo. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

Table of Contents

List of Figures

List of Tables

Abstract

This report discusses the design, use, cost, operation, and environmental effects of saltwater and brackish water cooling towers in comparison to freshwater towers as they are used for power plant cooling. It covers the following topics:

- A listing of global saltwater tower installations.
- An analysis of the performance and cost differences between fresh and saltwater towers.
- A review of operating and maintenance experience on a few operating saltwater towers at U.S. power plants.
- A review of environmental effects at sites with operating saltwater towers.

The use of high-salinity makeup water typically imposes a 4 to 8 percent performance penalty and a 35 to 50 percent cost penalty in comparison to freshwater towers of comparable cooling capability. Environmental effects of particular pertinence to salt/brackish water towers are primarily related to drift emissions, and they are largely confined to the near-field effects on plant buildings and equipment.

Keywords: Saltwater cooling towers, brackish water cooling towers, recirculating wet cooling, cooling tower drift, cooling tower performance, environmental effects of cooling towers.

Executive Summary

Introduction

The growing demand for the state's limited freshwater supplies has created pressure to reduce water use by thermal power plants, a major source of electricity in the state. A modern, highly efficient gas-fired power plant with cooling towers may use as much water as a community of 12,000 people. The majority of this water is used in the cooling system to capture waste heat and then routed to the cooling towers where the waste heat is dissipated to the air. This cooling process does not require high quality water, and in fact, water supplies with high salinity levels that are unsuitable for agricultural or municipal use without extensive treatment, may be used. Sources of high salinity water that could be used in cooling towers include naturally occurring brackish groundwater, irrigation return flows, produced water (groundwater which is brought up by oil and gas pumping), and seawater.

Another reason for interest in the use of high salinity water in cooling towers is that there are potential state and federal regulations that may require some of California's coastal plants, currently operating with once-through cooling technology to convert to closed-cycle cooling using cooling towers, presumably with seawater as the water source. Once-through cooling requires a significantly greater amount of water than closed-cycle cooling to be withdrawn from a water body, passed once through the power plant to capture waste heat and then discharged back into a water body. These potential regulatory developments include the United States Environmental Protection Agency, which is developing regulations under Section 316(b) of the Clean Water Act and the California State Water Resources Control Board, which has proposed a policy that will require some of these power plants to change cooling technologies.

Purpose

This study investigates potential issues associated with the choice of saline cooling tower makeup water, including effects on tower thermal performance and on the choice of materials of construction, both of which may affect the cost of the tower. In addition, operating and maintenance problems may arise and environmental problems may result, especially due to the salinity of the drift. Drift refers to water droplets that are carried out of the cooling tower with the exhaust air and have the same concentration of impurities as the water entering the tower.

Because of these concerns, this study seeks a better understanding of the effects on cost, performance, operating and maintenance requirements, and the environment impacts that may be encountered with the use of saltwater cooling towers for power plant cooling.

Project Objectives

This study provides information on the design, use, and operation of saltwater cooling towers. This information will assist the power plant developers, regulatory agencies, including the Energy Commission, and other stakeholders in evaluating alternative cooling systems for power projects in California.

Specifically, the study provides:

- A survey of saltwater tower installations in the United States and abroad.
- An analysis of performance and cost differences between freshwater and saltwater cooling towers.
- A review of operating and maintenance experience on a few saltwater towers at U.S. power plants.
- A review of environmental effects at sites with operating saltwater towers.

Project Outcomes

A list of salt- and brackish-water cooling towers was compiled from sources including the major cooling tower vendors, industry and government reports, trade journals, and personal contacts.

Tower performance information was obtained from vendor information and open literature references and was also estimated independently. Compared to freshwater, salt water's properties are less favorable for evaporative cooling. As a result, tower performance is slightly degraded and design modifications must be made.

A saltwater tower cost more than a freshwater tower for a given heat rejection capacity for two reasons. First, the performance degradation requires that the tower be slightly larger and consume slightly more fan power to achieve comparable performance. Second, the corrosive nature of salt water requires using different and more costly materials for tower and basin construction.

Operating and maintenance issues related to using of saltwater makeup were discussed during plant visits and telephone interviews with the operators of six plants and one vendor. Information was obtained on older towers, reflecting design and construction practices from the mid-1970s, and on newer towers, designed and built with the benefit of experience from the older units.

The environmental effects of saltwater tower operation have been studied for several decades. The authors reviewed the report literature and discussed some test programs conducted at plants that were visited.

Conclusions

The existing installations using salt water in cooling towers that were identified represent a wide range of sizes, applications, makeup water salinity and materials of construction. They provide ample evidence that utility-size cooling towers have been designed, built, and operated successfully using saltwater.

Consistent information on the effect on tower performance from circulating water salinity on emerged from the various information sources and the independent analytical estimates. The reduction in tower capability varies with circulating water salinity and with the operating liquid to gas ratio of the cooling water. The liquid to gas ratio refers to the proportion of liquid water to evaporated water. For salinities typical of seawater makeup to towers where the operating at 1.5 cycles of concentration (~ 50,000 parts per million) and at a typical liquid to gas ratio of 1 to 2, the correction factor is approximately 4 to 5 percent. Cycles of concentration refers to the number of times the solids in a particular volume of water are concentrated due to evaporation. The requirement to build the tower somewhat larger and to use more costly, corrosion-resistant construction materials increases cost about 35 to 50 percent compared to freshwater towers of the same capability.

The major conclusions regarding operation and maintenance are:

1. Recent installations of mechanical-draft cooling towers operating with high-salinity makeup water using corrosion-resistant material have operated satisfactorily, with no extraordinary operating and maintenance problems.
2. Operating results have been excellent, however long-term experience (greater than 15 years) is lacking.
3. Nearly all plants with high-salinity cooling towers, both natural and mechanical draft, have encountered accelerated corrosion on unprotected metal surfaces on buildings and equipment at the plant site near the towers.
4. Both mechanical- and natural-draft tower structures and basins constructed of concrete have experienced varying degrees of deterioration from exposure to salt water.

A number of environmental studies have been conducted by comparing deposition rates on surrounding land before and after the installation and operation of salt or brackish water cooling towers. Where particulate matter emissions from cooling towers are regulated, using of high salinity water in cooling towers will require purchasing air quality offsets to mitigate these effects.

All studies reach essentially the same conclusion that there were no significant increases observed in salt concentrations in soils or vegetation in the vicinity of the plants, nor any symptoms of environmental injury.

Recommendations

It is to be expected that an increasing number of cooling systems at new and existing plants are going to be designed, built, and operated on lower-quality water than in the past. It is recommended that the Energy Commission maintain active surveillance of the field over the next few years to continue to expand the body of information compiled in this study with the most up-to-date information as it becomes available.

Benefits to California

As California continues to balance the competing requirements for more energy with responsible stewardship of its water resources, the information from this study will assist the Energy Commission and other interested agencies to evaluating the trade-offs of cost, performance, water use, and environmental effects of salt water cooling towers.

Note: Unless otherwise indicated, all pictures and graphs in this report are the outcome of the research described herein.

1.0 Introduction

1.1. Motivation

There is increasing interest in using high-salinity water for power plant cooling towers for two reasons. First, the growing demands for electricity and water in the state have created pressure to consider using non-freshwater for power plant cooling at new and existing plants designed for closed-cycle cooling. Sources of high salinity water that could be used in cooling towers include naturally occurring brackish groundwater sources and produced water (groundwater that is produced with oil and gas pumping). Second, there are potential state and federal regulations that may require some coastal plants, currently operating with once-through cooling using ocean water, to convert to closed-cycle cooling using cooling towers, presumably with ocean water as the water source. These potential regulatory developments include the United States Environmental Protection Agency, which is developing regulations under Section 316(b) of the Clean Water Act and the California State Water Resources Control Board, which has proposed a policy that will require some of these power plants to change cooling technologies.

Potential issues associated with the choice of saline makeup include effects on tower thermal performance and on the choice of materials of construction, both which may affect the cost of the tower. In addition, operating and maintenance (O&M) problems may arise and environmental problems may be exacerbated, particularly from the salinity of the drift. In light of these concerns, the Energy Commission wants a better understanding of the effects on cost, performance, O&M requirements, and the environment that may occur with using saltwater cooling towers for power plant cooling.

1.2. Objective and Scope

This study provides information on the design, use, and operation of saltwater cooling towers and will assist the Energy Commission in evaluating alternative cooling systems for power projects in California.

The study consisted of five tasks:

- A survey of saltwater tower installations in the United States and abroad.
- An analysis of performance and cost differences between freshwater and saltwater towers.
- A review of O&M experience on a few saltwater towers at U.S. power plants.
- A review of environmental effects at sites with operating saltwater towers.
- Summary of study’s results.

1.3. Report Organization

Section 2 provides a brief review of cooling tower design, operation, and nomenclature for convenient reference. Section 3 analyzes performance differences between cooling towers using high-salinity makeup water and those using freshwater. Some simple rules of thumb from the existing literature are presented and evaluated, and some example calculations are presented for conditions relevant to California. Section 4 provides a list of seawater and brackish water cooling towers in operation in the United States and abroad and summarizes the experience that some power plants have had with saltwater cooling towers, in terms of both O&M and environmental effects. Section 5 presents the effect of using high-salinity water in cooling towers on cooling system cost. Section 6 summarizes the study's conclusions.

Three appendices contain a summary of seawater properties (Appendix A), a derivation of the performance characteristics for wet cooling towers (Appendix B), and detailed reports of on-site visits and interviews with plants currently operating with seawater or brackish water cooling towers (Appendix C).

.

2.0 Cooling System Basics

2.1. Closed-Cycle Wet Cooling Systems

Closed-cycle, or recirculated, wet cooling systems are usually the cooling system of choice for modern thermal power plants. The system, as shown schematically in
Figure 2-1, consists of two major components: (1) the steam condenser, usually a shell-and-tube surface condenser, and (2) a wet cooling tower, usually a mechanical-draft tower (recently more commonly of the counter-flow type, although the schematic shows a cross-flow configuration).

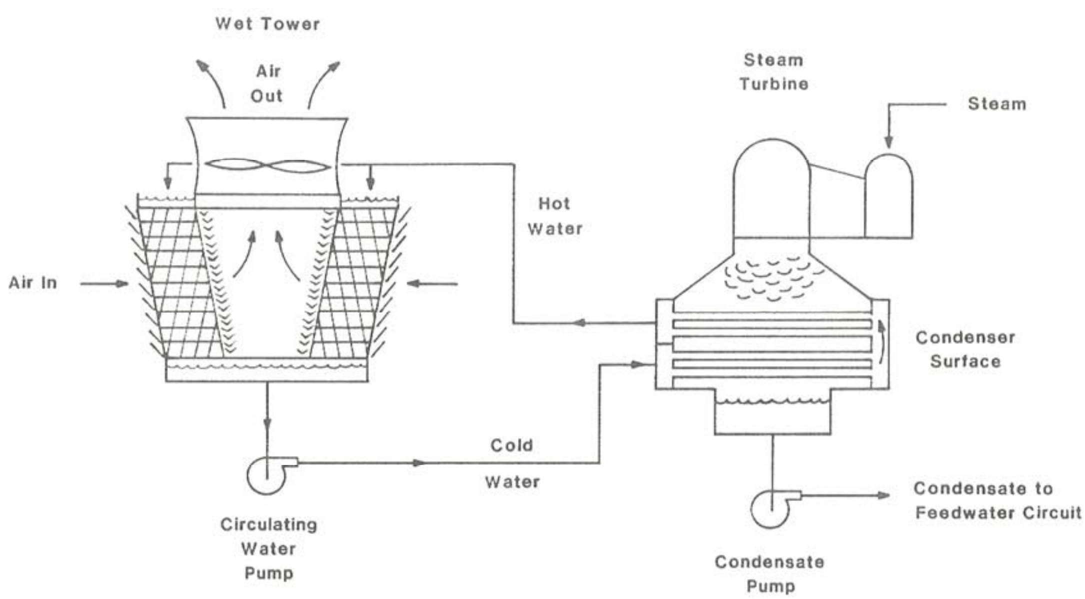

Figure 2-1. Closed-cycle wet cooling system
Source: Mitchell 1989

Steam from the low-pressure turbine exhaust flows into the condenser, where it is condensed on the outer surface of tubes with cooling water running through them. The condensed liquid is returned to the boiler to complete the power cycle.

The warmed cooling water leaving the condenser is sent to the cooling tower where it is cooled by heat rejection to the atmosphere, primarily by evaporation, and then *recirculated* to the condenser inlet. Figure 2-2 identifies the quantities involved in the cooling and water use processes and defines the important nomenclature.

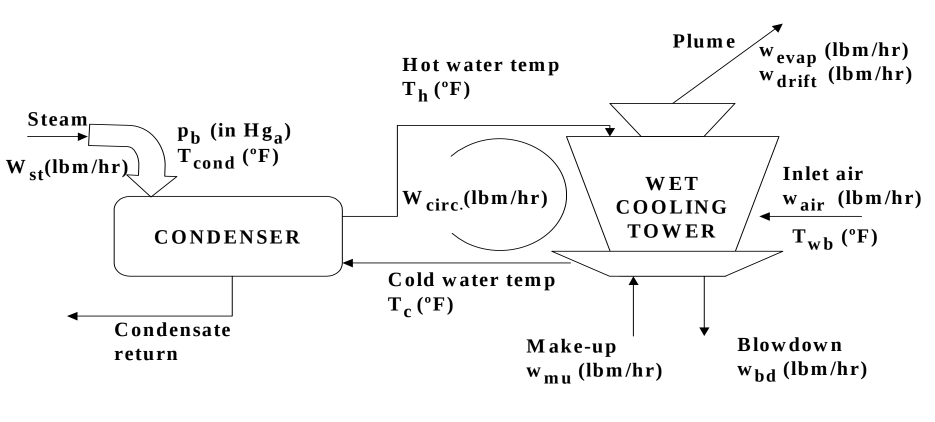

Figure 2-2. Closed-cycle cooling system mass and heat balance

The hot water from the condenser is introduced at the top of the tower and flows down through a “fill” section where it is brought into intimate contact with ambient air flowing counter to the direction of the falling water flow. Both sensible and latent heat transfer to the air cools the bulk of the water, which is then collected in a basin and returned to the condenser. The air leaves the tower, heated and humidified as an essentially saturated exhaust plume.

The cooling is achieved by the evaporation of a small fraction (1% to 2%) of the recirculating water flow. Therefore, once the system is filled, the only water withdrawn from the environment is makeup water in amounts sufficient to replace that lost to evaporation, blowdown,[1] and drift.[2]

2.2. Mass and Heat Balances

The elements of complete mass and heat balances are shown in Figure 2-2. The water balance on the cooling tower is given by

$$w_{mu} = w_{evap} + w_{bd} + w_d \qquad \text{(Eq. 2.1)}$$

where

w_{mu} is the makeup water; w_{evap} is water lost to evaporation, w_{bd} is blowdown water, and w_d is water lost to drift.

1. *Blowdown* is water discharged from the cooling system to control the buildup of dissolved and suspended materials that concentrate in the system as a result of the evaporation.

2. *Drift* refers to liquid water droplets entrained in the tower exit plume and released to the atmosphere.

The drift rate, w_d, is typically less than 0.002% of the circulating water rate (now usually specified at 0.0005% or less) as compared to the evaporation rate of 1% to 2% and the blowdown rate of 0.1% to 1%. Therefore, the drift rate is neglected in the following calculations.

2.2.1. Evaporation Rate

The rate of evaporation of water from the tower is related to the heat load on the tower, Q_{tower}, which is equal to the heat load on the condenser, Q_{cond}, given by

$$Q_{tower} = Q_{cond} = w_{circ} * c_p * (T_h - T_c) \qquad \text{(Eq. 2.2)}$$

with the evaporation rate given by

$$w_{evap} = Q_{tower} * f_{latent}/h_{fg} \qquad \text{(Eq. 2.3)}$$

where

f_{latent} = fraction of total heat rejected by latent heat transfer (0.9 is used here, but it can be lower depending on ambient conditions and design choice), and h_{fg} = latent heat of vaporization in British thermal units per pound-mass (Btu)/lbm); ~1000 Btu/lbm.

For an older steam plant such as might be considered for retrofit to closed-cycle cooling, typical plant efficiency might be 35%. Of the 65% waste heat, perhaps 15% would be dissipated in the stack gases and 50% in the condenser cooling water. The heat duty for the cooling system would be approximately 5,000,000 Btu/hour per megawatt (MW) of electric power generated. The values would differ slightly for the steam portion of combined-cycle plants, but these will be used for illustrative purposes. Therefore, the cooling system water consumption per MW can be calculated as

$$Q_{tower} = 5 \text{ x } 10^6 \text{ Btu/hr per MW} \qquad \text{(Eq. 2.4)}$$

$$w_{evap} = 5 \text{ x } 10^6 \text{ x } 0.9/1000 = 4{,}500 \text{ lbm/hr per MW or} \qquad \text{(Eq. 2.4a)}$$

$$w_{evap} \simeq 10 \text{ gallons per minute (gpm)/MW} \qquad \text{(Eq. 2.4b)}$$

2.2.2. Blowdown Rate

Blowdown rates are set to control scaling, fouling, and corrosion by limiting the buildup of impurities in the circulating water. This criterion is normally expressed in terms of maximum allowable cycles of concentration (n), defined as the ratio of the concentration of conserved species in the circulating water ($C_{i\ circ}$) to that in the makeup water ($C_{i\ mu}$):

$$n = C_{i\ circ}/C_{i\ mu} \qquad \text{(Eq. 2.5)}$$

The mass balance of species i in the tower requires that

$$w_{mu} \times C_{i\ mu} = w_{bd} \times C_{i\ circ} \qquad \text{(Eq. 2.6)}$$

$$w_{bd} = (w_{evap} + w_{bd}) \times (C_{i\ mu}/C_{i\ circ}) = (w_{evap} + w_{bd}) \text{ x } 1/n \qquad \text{(Eq. 2.7)}$$

Therefore,

$$w_{bd} = w_{evap} / (n - 1) \quad \text{(Eq. 2.8)}$$

Typical allowable cycles of concentration are from 3 to 6 (DiFilippo 2003). For n = 5 as a typical value, the required blowdown is

$$w_{bd} = [1/(5 - 1)] \times w_{evap} = 2.5 \text{ gpm/megawatt electrical (MWe)} \quad \text{(Eq. 2.9)}$$

and the required makeup is

$$w_{mu} = w_{evap} + w_{bd} = 12.5 \text{ gpm/MWe} \quad \text{(Eq. 2.10)}$$

Additionally, typical, consistent values of tower operating conditions are

Circulating water flow rate, w_{circ}: ~ 500 gpm/MWe
Condenser terminal temperature difference (TTD), $T_{cond} - T_h$: 6°F to 8°F
Tower range, $T_h - T_c$: 20°F to 24°F
Tower approach, $T_c - T_{amb.\ wet\ bulb}$: 8°F to 12°F

Therefore, the achievable steam condensing temperature is given by

$$T_{cond} = T_{amb.\ wet\ bulb} + \text{Approach} + \text{Range} + \text{TTD} \quad \text{(Eq. 2.11)}$$

For an ambient wet bulb temperature of 70°F, values in the typical ranges of TTD = 7°F, Range = 22°F, and Approach = 10°F would provide a condensing temperature of 109°F, corresponding to a turbine back-pressure of 2.5 inches of mercury (in. Hga). Tower approach temperature depends on design ambient conditions, as well as many other factors including tower type, size, fill choice, and air flow. In general, warmer, more humid conditions lead to lower approach temperatures, as in the southeastern United States and cooler, drier climates lead to higher ones, as in the northern and western regions.

2.2.3. Effect of Water Properties

The properties of high-salinity water differ from those of freshwater, and those differences lead to slightly altered cooling tower performance. For purposes of this report, *high-salinity water* refers to seawater, concentrated seawater, and lower-salinity or brackish waters found in bays or estuaries or as groundwater. The chemical composition of "normal seawater" is given in Table A-1 of Appendix A. Other tables in the appendix provide values of several thermo-physical properties important to the performance of cooling towers for seawater of doubled concentration and of freshwater (Office of Saline Water 1959).

The derivation in Appendix B provides a fundamental discussion to help readers understand the effect of these property differences on tower performance. The effects of specific properties are summarized here.

2.2.4. Vapor Pressure

The presence of salts in water reduces the vapor pressure at any given temperature, as seen in Figure A-2a and A-2b in Appendix A. This reduces the driving force for evaporation and, in effect, lowers the enthalpy of saturated air at the local water temperature, which lowers the driving force. Therefore, a larger fill volume or a higher performance fill will be required to transfer the same amount of heat.

2.2.5. Surface Tension

The surface tension for seawater is somewhat higher than for freshwater (Figure A-3; Appendix A). This higher surface tension tends to facilitate the breakup of the film, create smaller droplets, and slightly increase the interfacial area per unit of fill volume, (a). This tendency would slightly enhance the performance of seawater compared to freshwater. The performance of drift eliminators is also dependent on surface tension In general, an increase in surface tension will slightly improve the performance of drift eliminators.

2.2.6. Dynamic Viscosity

The dynamic viscosity of seawater is slightly higher than for freshwater (Figure A-4; Appendix A). This higher viscosity may result in slightly thicker films on the fill and a minor reduction in performance compared to freshwater.

2.2.7. Thermal Conductivity

The thermal conductivity of seawater is lower than that of freshwater for the temperature range relevant to cooling tower operation (Figure A-5, Appendix A). This may result in a slightly higher temperature drop across the liquid films. The resistance to heat transfer associated with the temperature drop across the film is normally neglected in simplified analyses and conventional performance correlations. The decreased liquid thermal conductivity may result in a slight decrease in performance for salt water in comparison to fresh water.

2.2.8. Density and Specific Heat

At a given temperature, the density of seawater is about 2% to 3% greater than freshwater, while the specific heat is about 4% less. (Figures A-6 and A-7; Appendix A). Therefore, a given volume of seawater has slightly less cooling capacity than freshwater. For a given heat load, either the water flow or the range must be increased somewhat for a saltwater tower. These effects are all minor compared to the effect of vapor pressure.

Section 3 will provide the results of some tests, analyses, and resulting rules of thumb for adjusting the expected performance of freshwater cooling towers to account for the use of salt water as the cooling medium.

3.0 Cooling Tower Performance

3.1. Effect of Salinity on Cooling Tower Performance

The thermal performance of cooling towers using salt or brackish water will differ from that of an identical tower under identical conditions using freshwater for cooling. As was discussed in detail in Section 2, this difference results from variations in the thermodynamic and transport properties of salt water as a function of salinity. Of these, the most important is vapor pressure.

The following paragraphs review several approaches that can be used to account for the effect of salinity on cooling tower performance. These include a simple correction factor and some simple “rules of thumb” for adjusting the design specifications.

3.2. Seawater Correction Factor

A thorough discussion of the effect of salt water on cooling tower performance was presented in a 1991 Marley publication (Ting and Suptic 1991). The recommended approach is to rate the cooling tower as if it were using freshwater and then apply a correction factor. Figure 6 of Ting and Suptic (1991) is reproduced here as Figure 3-1 (with an estimated curve for a salinity of 50,000 parts per million [ppm] added). The correction factor is plotted against the liquid-to-gas flow rate ratio (L/G) for a water salinity level twice that of seawater. The factor varies from 7% at an L/G = 1 to just under 2.5% at an L/G = 5.5. The reason for the decrease in the effect of salinity with increasing L/G can be seen by reference to Figure B-4 in Appendix B. Towers for a given range and wet bulb temperature designed for high L/G ratios have much lower KaV/L and operate at much higher approach temperatures. The magnitude of the driving force, ($h_{sat\,@\,Tw}$ – h_{air}), is correspondingly larger and the effect of a given decrease on the vapor pressure at the water surface, $h_{sat\,@\,Tw,}$ is also correspondingly less.

3.3. Rules of Thumb

Some rules of thumb have been put forward by the industry to estimate the reduction in cooling tower capability (or alternatively, the increased tower size required to meet the same heating load) incurred with saltwater operation.

The simplest of these (Aull 2005) suggests a 5% capability reduction for a salinity of 50,000 total dissolved solids (TDS). Similar estimates (Eftekharzadeh et al. 2003) suggest a loss in performance of 5.4% at a salinity of 50,000 TDS. Reference is made in that publication to a Fluor (Fluor R/D Division 1957) paper which recommends increasing the design wet bulb by 0.055°C (~ 0.1°F) for each 4,000 ppm of dissolved solids. For seawater operating at 1.2 to 2 cycles of concentration, this corresponds to an increase in the design wet bulb of 0.55°C to 1.1°C (~ 1°F to 2°F).

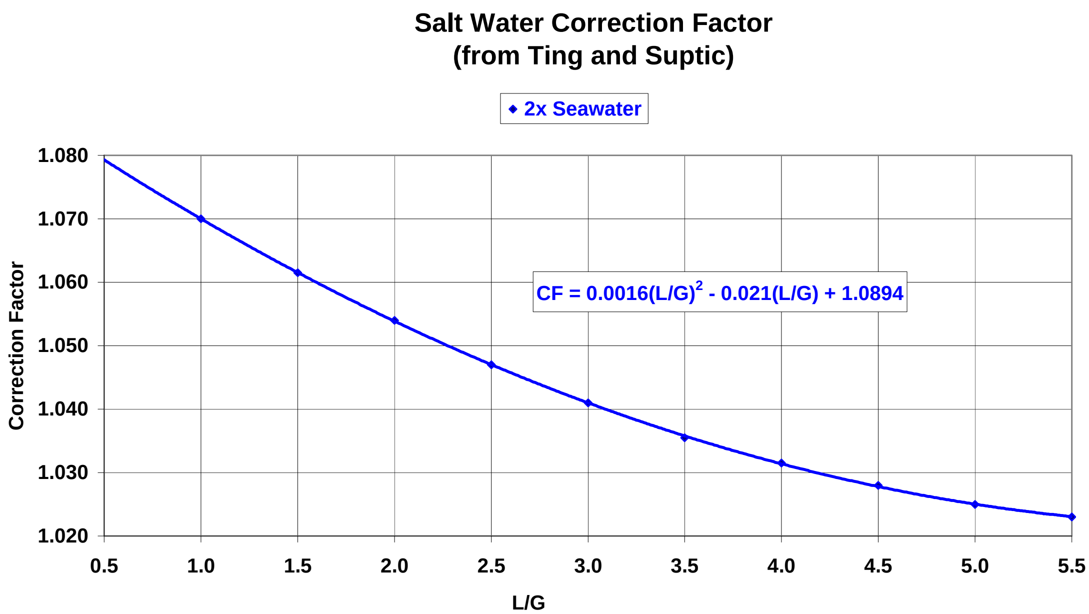

Figure 3-1. Salt water correction factor

Source: Ting and Suptic 1991

Figure 3-1 gives the recommended correction for a 2x seawater salinity or approximately 70,000 ppm. Assuming a linear correction factor adjustment with salinity, the corresponding line for 50,000 ppm would give a correction factor between 1.05 and 1.054 at approximately an L/G = 1 which seems appropriate for the conditions of interest to the study (Eftekharzadeh et al. 2003).

Finally, using the rule of thumb suggested in the Fluor reference (Fluor R/D Division 1957) of increasing the wet bulb temperature by 0.1°F for each 4000 ppm of dissolved solids, assume a 1.25°F increase for a TDS of 50,000 ppm.

3.4. Calculated Capability with Saline Water Makeup

The CTI Workbook (CTI 2005) was used to calculate the capability correction implied by the recommendation to increase the wet bulb temperature by 0.1°F for each 4000 ppm increase in circulating water salinity.

The calculation proceeds as follows. For a base (freshwater) case with design specifications of

Wet Bulb Temperature: 75°F

Cold Water Temperature: 90°F

Hot Water Temperature: 120°F

the CTI Workbook, gives the following KaV/L value and corresponding fill coefficient, C, for a range of L/G, as displayed in Table 3-1.

Table 3-1. Base case (freshwater) results

L/G	KaV/L	C (n = -.7)
0.6	1.005	0.703
0.8	1.079	0.923
1	1.168	1.168
1.5	1.500	1.992
2	2.233	3.628

The fill is assumed to have a characteristic of

$$KaV/L = C * (L/G)^{-0.7} \qquad \text{(Eq. 3.1)}$$

The same computation is then performed for (1) an assumed wet bulb temperature of 76.25°F (increased by 1.25°F per recommendation), and (2) the same fill characteristics.

The L/G at which the same cold water temperature can be obtained is determined and compared to the freshwater values in Table 3-1. The ratio of $\{(L/G)_{salt}/(L/G)_{fresh}\}$ is the corresponding capability correction factor. This approach neglects the minor affects of variation in all thermophysical properties with salinity and attempts to simulate the effect of the reduced vapor pressure with an increased wet bulb temperature. The results are tabulated in Table 3-2 and plotted on the same coordinates as Figure 3-1 for comparison to the published correction factor and show reasonable agreement. This suggests that for the usual range of circulating water salinities, operating temperature ranges, and design points the correction curve and the recommended elevation of the wet bulb temperature are consistent.

Table 3-2. Comparative performance—fresh- vs. saltwater makeup

L/G (Fresh)	C	L/G (Saline)	Ratio L/G
0.6	0.671	0.57	1.053
0.8	0.88	0.7625	1.049
1	1.11025	0.955	1.047
1.5	1.8725	1.442	1.040
2	3.32	1.936	1.033

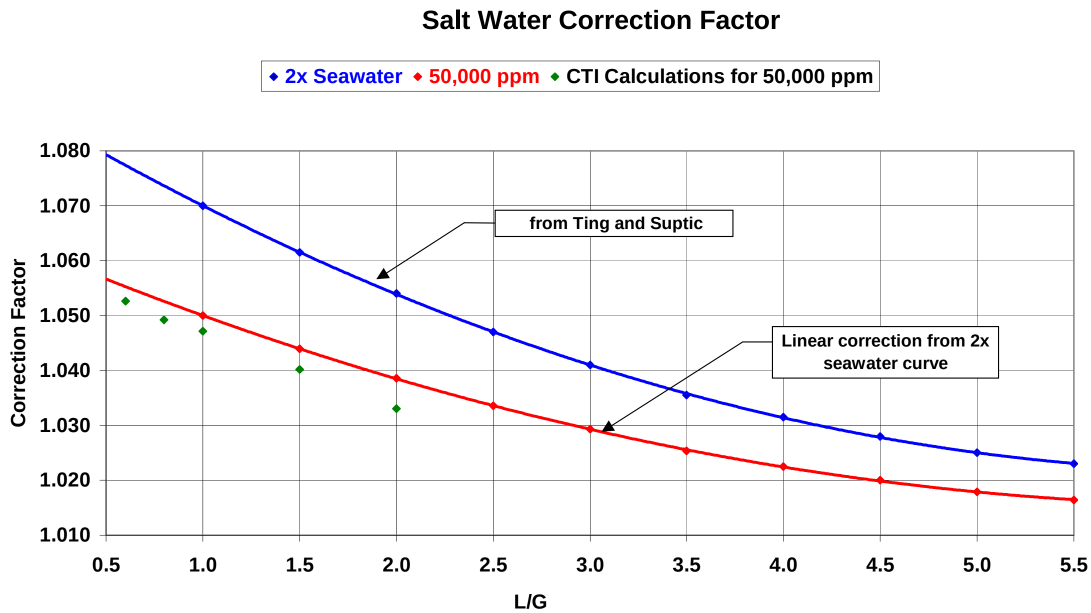

Figure 3-2. Effect of salinity on correction curve

Source: John S. Maulbetsch, Consultant, and Michael N. DiFilippo, Consultant.

Therefore, on the bases of literature recommendations and a simple computational correction, a capability reduction of approximately 5% appears to be reasonable for typical conditions. This additional capability can be provided in a variety of ways, including the following:

- Increased cell plan area (width or length).
- Additional cell or cells.
- Increased air flow (fan power).

The effect on design, materials selection, and cost will be presented in Section 5.

4.0 Experience with Saltwater Towers

4.1. High-Salinity Operation

The use of cooling towers on high-salinity makeup water is not new. There are many such installations in the United States and abroad, at both power plants and industrial facilities.

The makeup waters range from seawater with a nominal salinity of around 35,000 ppm (milligrams per kilogram [mg/kg]; see Table A-1 in Appendix A) to brackish waters with salinities ranging from a few hundred (or a few thousand) ppm in the case of groundwater or from a few thousand ppm to nearly full seawater concentration in the case of bays or estuaries. Here the salinity can vary significantly on a time-scale ranging from seasonal to hourly under the influence of rainfall, storms, and tides.

The salinity of the circulating water in the cooling system is that of the makeup water times the cycles of concentration, which is controlled by the rate of blowdown from the system (See Eq. 2-5). Typically towers with high-salinity makeup (approaching seawater salt content) are operated at low cycles of concentration in the range of x 1.5 to x 2. In the case of seawater this results in a circulating water concentration of 50,000 to 70,000 ppm. While there have been some examples of operating a tower at 100,000 ppm, this is rare. Some inland towers operate with brackish groundwater or reclaimed wastewater as makeup with salinities as high as 2,000 to 5,000 ppm. In some cases, particularly at plants with zero liquid discharge constraints, the towers will run at 5 to 10 cycles of concentration to reduce the volume of blowdown in order to reduce the cost of the final evaporation/ crystallization steps prior to disposal of the final solid waste products.

4.2. Existing Installations

Table 4-1 on the following pages gives examples of existing towers operating on salt or brackish water. The list is not complete but is based on information from two major tower vendors (GEA and SPX-Marley), plus a variety of other sources and personal contacts.

The table attempts to provide information on tower size, operating point, construction materials, and source water. In many instances, this information was not available or easily obtained. The essential message from the accumulated information, however, is that towers of a wide range of size, application, construction materials, and makeup water quality have been designed, installed, and operated for several decades.

Table 4-1. Saltwater tower installations

Client	Project/Location	Circ. Water flow gpm	Hot Water Temp. F	Cold Water Temp. F	Wet Bulb Air Temp. F	Approach F	Range F	Fill Type	Tower Construction	Tower Type	Year
Koch / Siemens	Ribatejo/Portugal	91,812	88	69	55	14	18	Film / trickle grid	Concrete	Wet, fan assisted	2005
Siemens	BASF	70,992	88	68	47	21	20	Film / trickle grid	Concrete	Wet, natural draft	2005
Koch / Siemens	Ribatejo/Portugal	183,628	88	69	55	14	18	Film / trickle grid	Concrete	Wet, fan assisted	2002
Plant (Lansing) Smith Unit #3 (575 MW; gas-fired combined-cycle	Lynn Haven, FL	125,000	107	86	80	6	21	Low clog	FRP	Mech. draft; counterflow; 10 cells	2002
Juball United Petrochem	Suadi Arabia	292,554									2002
GB3	Malasia	149,560									2001
Endesa	Spain	124,181									2001
Petrobras	Brazil	241,580									2001
Siemens	Seaband II/GB	86,838	87	69	52	17	18	Trickle grid	Wood	Wet/dry (hybrid)	2000
Esso Singapore	Singapore	61,853									2000
Endesa	Spain	70,902									2000
BASF	BASF	52,821	86	75	66	9	11	Film	Wood	Cells, wet	1999
Duke Fluor Daniel	USA	167,980	89	76	64	13	13	Film	Wood	Cells, wet	1999
H. B. Zachary	Calpine/USA	205,976	90	75	67	8	15	Trickle grid	Wood	Cells, wet	1999

Table 4-1. Saltwater tower installations (cont.)

Client	Project/Location	Circ. Water flow gpm	Hot Water Temp. F	Cold Water Temp. F	Wet Bulb Air Temp. F	Approach F	Range F	Fill Type	Tower Construction	Tower Type	Year
Florida Power Corp.	Crystal River	295,295									1999
Kaitim Parna Industry	Indonesia	74,670									1999
Esso Singapore	Singapore	17,956									1999
Bibb & Associates	LS Power / USA	83,990	105	81	66	15	24	Film	Wood	Cells, wet	1998
Bechtel Corporation	USA	287,963	104	89	80	9	15	Film	Wood	Cells, wet	1998
Plant Watson Unit #4	Gulfport, MS	125,000						Mixed: high performance + anti-fouling	Wood and FRP	Mech draft: couterflow; 10 cell helper tower	1998
E.G.A.T.	Thailand	211,273									1998
Bechtel Corporation	Rocksavage/GB	158,463	87	66	30	36	21	Film	Wood	Wet/dry (hybrid)	1997
Dow Engineering Rotterdam	Elsta, Temeuzen/NL	67,787	76	62	48	15	14	Film	Wood	Cells, wet	1997
GEM Methanol	Trinidad	54,962									1997
Ecoelectrica	Puerto Rico	9,593									1997
Ecoelectrica	Puerto Rico	155,525									1997
Amata Egco B	Thailand	53,446									1996

Table 4-1. Saltwater tower installations (cont.)

Client	Project/Location	Circ. Water flow gpm	Hot Water Temp. F	Cold Water Temp. F	Wet Bulb Air Temp. F	Approach F	Range F	Fill Type	Tower Construction	Tower Type	Year
Siemens	Killinghoime/GB	2 x 103,441	81	58	31	27	23	Splash	Concrete	Wet/dry (hybrid)	1995
Stanton Energy #2	Florida	200,292	114	91	78	13	23				1995
E.G.A.T.	Thailand										1995
Holly Sugar	/USA	5,000	85	72	62	10	13	Splash	wood	cells, wet	1994
Powergen, Connah's Quay	UK	375,073									1993
E.G.A.T.	Thailand	312,298									1993
Monsanto Enviro-Chem	/USA	39,893	110	90	80	10	20	Film	wood	cells, wet	1992
Western Sugar	/USA	10,001	102	76	67	9	26	Splash	wood	cells, wet	1992
Zurn Nepco	/USA	31,996	103	85	70	15	18	Film	wood	cells, wet	1992
ABB-Lumas	/USA	25,874	120	85	78	7	35	Splash	wood	cells, wet	1992
Atlantic City Electric Co. (NJ)	B.L. England	71,508							concrete	natural draft;	1992
BE&K	/USA	17,000	110	95	75	20	15	Splash	wood	cells, wet	1991
Parson-ARCO	/USA	39,994	100	75	65	10	25	Film	wood	cells, wet	1991
Delano Biomass	California	19,427	98	83	73	10	15				1991
BASF	Belgium	63,689									1991
Florida Power Corp.	St. Petersburg	685,210									1990
CEGB, Killinghoime	UK	205,879									1990
Delmarva Power & Light	Delaware	202,796	117	90	79	11	27				1989
St. John's River Power Park Unit # 2 (624 MW; coal)	Jacksonville (FL)	247,700	114	90	80	10	24	orig--low fouling; now--high performance	concrete	Natural draft; counterflow	1988
Palo Verde III	Arizona	687,857	119	87	77	10	32				1987
Houston Lighting & Power	Texas	241,352	110	94	82	12	15				1987

Table 4-1. Saltwater tower installations (cont.)

Client	Project/Location	Circ. Water flow gpm	Hot Water Temp. F	Cold Water Temp. F	Wet Bulb Air Temp. F	Approach F	Range F	Fill Type	Tower Construction	Tower Type	Year
St. John's River Power Park Unit # 2 (624 MW; coal)	Jacksonville (FL)	247,700	114	90	80	10	24	low fouling	concrete	Natural draft; counterflow	1986
Palo Verde II	Arizona	587,857	119	87	77	10	32				1986
Stanton Energy #1	Florida	200,292	114	91	78	13	23				1986
Palo Verde I	Arizona	587,857	119	87	77	10	32				1985
SIAPE	Tunisia	35,139									1985
Gujarat Electricity Board	India	145,387									1984
Al Nawasi	Kuwait Oil Co/Kuwait	10,203	103	95	88	7	8	Ceramic	concrete	cells, wet	1983
Fluor Daniel	Saudi Petrochem. Co. Jubail/SAR	50,180	125	98	92	6	27	Film	concrete	cells, wet	1983
DRAVO	Sudai Petrochem. Co. Jubail/SAR	35,989	121	98	92	6	23	Grids	concrete	cells, wet	1983
Parish Unit # 7 (615 MW; coal)	Houston, Tx								concrete	mechanical draft; round; cross-flow	1982

4.3. Environmental Effects

All closed cycle wet cooling systems with cooling towers have some environmental effects. Those normally considered are blowdown, drift, noise, and visible plumes.

Of these, noise and visible plumes from salt/brackish water towers are no different from those from freshwater towers. As such, they will not be discussed further in this study.

The effects from blowdown and drift differ from those from freshwater towers to the extent that the salinity of the circulating water is higher.

4.3.1. Blowdown

The environmental issues related to the discharge or treatment of blowdown from salt or brackish water cooling towers appears to differ little from those for freshwater towers. However, it should be noted that discharge options are limited.

1. High salinity (50,000 to 70,000 ppm) cannot be discharged to municipal water treatment facilities.
2. Treatment, volume reduction, or on-site disposal of the blowdown steam would be prohibitively expensive. For towers operating on seawater makeup at two cycles of concentration, the blowdown rates are very high—on the order of 10 gpm per MW, or 5000 gpm for a 500 MW steam plant. The cost of evaporation ponds, even if the plant were located in an area with a high net annual evaporation rate, would be extremely high—on the order of a few hundred million dollars. The cost of evaporator/crystallizer systems, frequently used on zero-discharge plants but at far lower input rates, would be equally unacceptable.
3. For plants discharging to the nation's waterways under a National Pollutant Discharge Elimination System (NPDES) permit, the stringency of the rules can vary from state to state and from site to site. For ocean discharges, at least under the California Ocean Plan, the increased levels of dissolved solids do not appear to be regulated, with the exception of those specified toxic species of arsenic, copper, mercury, silver, and zinc. For power plants (and other high-volume discharges) limitations on both effluent concentrations and total mass discharges are imposed according to procedures and formulas documented in the plan.

A comparison with ocean desalination plants may be illuminating. Typical values for desalination plant capacity range from 20 to 112,000 acre-feet per year and "recovery" (defined as gallons of freshwater per gallon of seawater) from 15% to 50%, depending on the technology used. Assuming a plant size of 100,000 acre-feet per year (~90 million gallons per day) and a recovery rate of 50%, the desalination plant would have a discharge stream with a salt concentration of 70,000 ppm and a flow rate of about 620,000 gpm (California Coastal Commission 1993). This would be roughly equivalent to the blowdown from seawater cooling towers operating at two cycles of concentration at twelve 500 MW power plants operating at two cycles of concentration.

4.3.2. Drift

Elevated salinity in the circulating water could affect drift emissions and their subsequent environmental effects in two ways.

First, if the modified properties of the water affected the performance of the drift eliminators themselves, the amount of drift emitted could change. However, inquiries with a drift eliminator manufacturer revealed that "there should be no difference in the efficiency of drift eliminators, since the drift capture efficiency of a drift eliminator section is a function of droplet size, air velocity, and workmanship of installation…as long as the saltwater concentration does not lower the water's surface tension significantly (R. Aull 2005)." Appendix A-5 indicates that the surface tension for salt water is slightly higher than it is for freshwater, so for the same drift eliminators and the same quality of installation workmanship, the drift emissions should be unchanged.

Second, the drift droplets have a higher salinity, so the mass emission of salt increases while the emission of the drift itself remains unchanged. This introduces two concerns: (1) the amount of fine particulate matter (PM_{10} and $PM_{2.5}$)[3] released into the atmosphere as the drift droplets evaporate will increase, and (2) the mass deposition of salt on neighboring soils, vegetation, buildings, vehicles, and equipment will be higher than for freshwater towers. The effect of near-field salt drift on equipment at the plant site will be discussed in the following section.

PM₁₀ Emissions

Cooling tower drift is often discussed in the context of PM_{10} emissions. National ambient air quality standards (NAAQS) limit PM_{10} concentrations to an annual arithmetic mean of 50 micrograms per cubic meter ($\mu g/m^3$), or 150 $\mu g/m^3$ in any 24-hour period (U.S. Environmental Protection Agency 2006). To maintain these levels, emissions limits are placed on point sources; in this case, 100 tons per year. The agency has defined an "emissions factor" for cooling tower drift emissions of 1.7 lb/10^3 gallons of recirculating water flow. This definition is based on the assumption that cooling tower drift eliminators limit drift to 0.02% of the recirculating water flow rate. It is further assumed that all of the drift evaporates in the atmosphere and that <u>all</u> the dissolved and suspended matter in the drift is released as PM_{10}.

The simple application of this factor and that assumption to a wet cooling tower with seawater makeup operating at 1.5 cycles of concentration (drift salinity of 52,500 ppm) and a circulating water flow of 250,000 gpm (typical for a 500 MW steam plant) gives an emission rate for PM_{10} of approximately 4700 tons per year for an 80% capacity factor.

By contrast, a tower with fresh water makeup with an assumed dissolved solids concentration of 500 ppm operating at 10 cycles of concentration would have a drift salinity of 5,000 ppm or less than 1/10th that of a tower with seawater makeup.

3. Particles with a mean aerodynamic diameter less than or equal to 10 (or 2.5) microns

However, these assumptions have been challenged as unrealistically conservative in several analyses (Micheletti 2006; Reisman and Frisbie 2002). Even the U.S. Environmental Protection Agency (U.S. EPA) has characterized them as "conservatively high" (U.S. Environmental Protection Agency 1995). Specifically,

1. Modern drift eliminators have drift rates of 0.002% to 0.0005%, a factor of x10 to x40 lower than the 0.002% assumed in the agency's "emission factor";
2. Calculations based on accepted drift drop size spectrum data (as those, for example, in Figure 4-1) and plausible assumptions about the density and shape of the particles remaining following evaporation of the drift droplets suggest that only a small fraction (less than 15%) of the residual particles will have an aerodynamic diameter of less than 10 μ (Micheletti 2006).

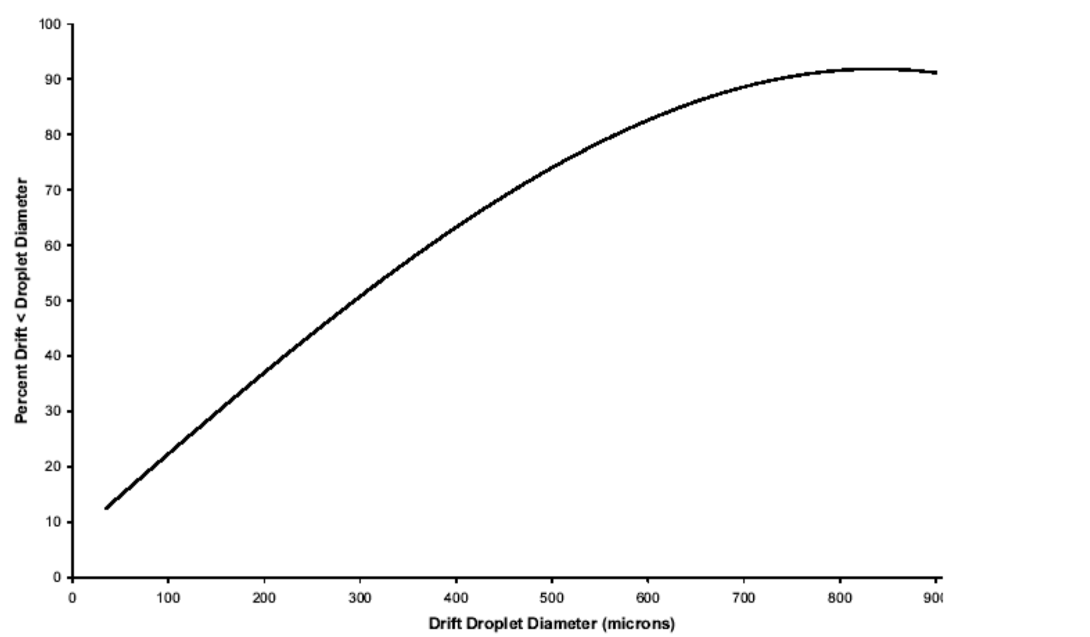

Figure 4-1. Drift droplet size spectrum

Source: Micheletti 2006

Using a value of 0.002% and a 15% PM_{10} fraction, the calculated PM_{10} emission rate for the 250,000 gpm seawater tower is reduced to 70 tons per year. It should be recognized that these assumptions and resulting calculations are uncertain. Drift rates are a function of the quality of installation and state of repair of drift eliminators and can be higher in practice than they are under ideal conditions. In addition, the drop size spectrum can change with different drift eliminator designs and with age and condition. Additionally, some fraction of the drift will inevitably hit the ground or surrounding structures and the dissolved material in those drops will not be released into the atmosphere. Only careful on-site measurements can give a credible estimate of the PM_{10} emission rates from any cooling tower.

Under some regulatory conditions it may be necessary to purchase offsets for PM10 emissions in order to obtain permission to operate. It some areas there may be no offsets available. Even if there are, the cost, although variable, can be quite high. Costs reported in minutes of a South Coast Air Quality Management District Board Meeting (SCAQMD, 2005) show an increase from ~$4,000/lb/day to over $25,000/lb/day in 2004. For the situation described above with PM10 emissions of 4,700 tons/year (equal to approximately 26,000 lb/day), this cost range would correspond to offset costs of from $103 million to $650 million. Even at the lower PM 10 emission rate of 70 tons per year, the cost range is $1.5 to nearly $10 million.

Salt Deposition

The assessment of the impact of emissions from evaporative cooling systems must be done with an understanding of the background conditions that exist at the site. For instance, in the case of a coastal power plant, while cooling tower drift emissions will contribute to the ambient salt levels (i.e., deposition and concentration), there is already natural salt in the atmosphere. It is also likely that native vegetation has adapted to this environment and is more salt tolerant than natural species which are further inland. Further, the presence of sea salt in the air may already be having some local effects on the surrounding community, in the form of generalized corrosion or other effects.

Studies of ambient or baseline conditions associated with prospective cooling system operation and impacts have been conducted in a number of situations. Some of these are cited in Table 4-2.

Table 4-2. Example cooling tower environmental impact assessments

Utility	Site	Proposed Cooling System
Atlantic City Electric	B. L. England – Coal-Fired, NJ (Wilber 1975)	Natural Draft - Brackish Water
General Public Utilities	Forked River Nuclear, NJ (Shofner et al. 1973)	Natural Draft – Brackish Water
Potomac Electric	Chalk Point – Coal-Fired, MD (Davis 1979)	Natural Draft – Brackish Water
Pacific Gas & Electric	Geysers Geothermal, CA PG&E 1979)	Mechanical Draft – Boron and Salts
Oak Ridge National Laboratories	K-25 Gaseous Diffusion Plant, TN	Mechanical Draft - Chromates
Pacific Gas & Electric	Pittsburg – Oil Fired, CA	Mechanical Draft – Brackish Water
Florida Power Corp.	Turkey Point Nuclear, FL	Spray Systems, Mechanical Draft – Seawater

Source: John S. Maulbetsch, Consultant, and Michael N. DiFilippo, Consultant

Beyond specific cooling-system studies, a number of atmospheric or background assessments have been conducted for the purpose of better understanding issues such as formation and role of condensation nuclei, impacts on visibility, assessment of corrosion issues, and others (Porter et al. 2000; Wilber 1974; Woodcock 1952; Woodcock 1953; Boyce 1954; Rossnecht et al. 1973). Many, but not all of the studies have focused on coastal environments, where naturally occurring salt is produced from wind and wave action.

Cooling Tower Emissions Impacts

Given these levels of naturally occurring salts in coastal environments, it is important to document, on a site-specific basis, these background levels and contrast them against expected contributions from cooling systems. Background characterization would include the following:

- Ambient concentration and deposition of salts that are expected in the cooling tower circulating waters.
- Concurrent wind speed, wind direction, and humidity history. (Note that humidity is important relative to the size and fate of hydroscopic aerosols like sea salts and resultant condensation nuclei.)

Cooling tower operating profiles (continuous, intermittent, etc.) and cooling tower emissions (droplet size, drift emissions rate, etc.) determined from source term measurements can be made.

Published studies indicate that background salt concentrations vary considerably from, for example, 100 $\mu g/m^3$, with horizontal mass fluxes ranging from 500–1000 micrograms per square meter per second ($\mu g\ m^{-2}\ sec^{-1}$) in the Hawaiian Islands (Porter et al. 2000) to ambient salt concentration in near coastal environments in the southeastern United States of 2–50 $\mu g/m^3$ (Wilber et al. 1983). Those measurements were conducted under lighter winds (2–4 meters per second [m/s]) and shorter fetches than typically occur around the Hawaiian Islands.

These values are contrasted against vertical fluxes (i.e., deposition rates) of salts modeled from mechanical draft cooling towers of 50–500 $\mu g\ m^{-2}\ sec^{-1}$ within 100 meters of the source (Wilber and Webb 1983). Therefore, drift from cooling systems can be more or less significant, depending on background circumstances.

Environmental Effects

A number of environmental effects studies have been conducted by comparing deposition rates on surrounding land before and after the installation and operation of salt or brackish water cooling towers.

Appendix C-1, which documents the site visit to St. Johns River Power Park, contains a brief description of the results of pre- and post-operation field monitoring of deposition and uptake at plots in the vicinity of the towers. The conclusions, summarized there, are repeated here.

> "The conclusions, documented in detail in permitting reports are summarized as follows :

- Some increased NaCl concentration was found in deposition samples after Unit #2 began operation.
- No significant increases were seen in soil or vegetation samples.
- Vegetation at the site with highest deposition was apparently unaffected.
- No injury symptoms related to NaCl were observed on pasture grass or other vegetation on or in the vicinity of the Power Park.

These results are consistent with those reported elsewhere in numerous studies. The most extensive study was the Chalk Point Cooling Tower Project conducted in the late 1070's by the Maryland Power Plant Research Program (Davis 1979). The results, summarized in both U.S. EPA (2000) and Eftekharzadeh et al. (2003), found "no measurable increase in soil salts concentration in the tobacco fields near the facility" and no instances [including Chalk Point] where cooling tower operation has resulted in measurable productivity losses in agricultural crops or measurable damage to ornamental vegetation."

4.4. Operating Experience

Information on performance and O&M experience was solicited through visits and telephone interviews with the staff of plants equipped with seawater or brackish water towers. These included:

<u>Plants visited</u>

- St. Johns River Power Park, Jacksonville, Florida
- Plant Smith, Lynn Haven, Florida
- Plant Crist, Pensacola, Florida
- Plant Watson, Gulfport, Mississippi

<u>Telephone interviews</u>

- Pittsburg Power Plant, Pittsburg, California
- Palo Verde Nuclear Generating Station, Palo Verde, Arizona
- GEA Integrated Cooling Technologies, Lakewood, Colorado

Complete visit and interview reports are found in Appendix C. The major conclusions are summarized below.

1. Recent installations of mechanical cooling towers have used fiberglass reinforced plastic (FRP) structure, PVC fill and corrosion-resistant fittings (high grade stainless steel, silicon bronze (coated), titanium). Operating results have been excellent, but long-term experience (> 15 years) is lacking.

2. Nearly all plants with high-salinity cooling towers, both natural and mechanical draft, have encountered accelerated corrosion on unprotected metal surfaces on buildings and equipment at the plant site near the towers.
3. Both mechanical and natural-draft tower structures and basins constructed of concrete have experienced varying degrees of deterioration from exposure to salt water. In some cases, very extensive repairs have been required. Chloride-resistant concrete and rebar is recommended for high-salinity applications.
4. In some cases, the high-salinity water was also high in suspended solids at certain times. This often led to plugging of high-efficiency fill and deteriorated performance. This effect is unrelated to the salinity levels.
5. It must be recognized that some high TDS waters may result from operation with moderate TDS makeup and high cycles of concentration. This usually results in water chemistry that is very different from sea or brackish waters, and may be high in scaling constituents. In these cases, more elaborate water treatments, such as scale inhibition or softening, may be required.

5.0 Salt Water Cooling System Costs

In comparison to cooling systems designed to operate on fresh water, salt or brackish water systems are more expensive. This is the result of several factors.

- The properties of sea water lead to reduced thermal capability for a given tower.
- The higher levels of dissolved and suspended solids in salt or brackish water sources may require the use of lower efficiency, "low-clog" fill.
- The aggressive nature of the higher salinity water normally requires the use of more corrosion resistant, and more expensive, materials for cooling system components and hardware.
- Under some circumstances, deterioration of tower or basin materials may occur resulting in costly maintenance or repair.
- The effects of salt drift deposition may result in higher costs for cleaning, protection or repair of equipment, structures and surfaces in the vicinity of the tower.

Many of these costs are highly variable, site-specific and hence difficult to generalize. The following sections will briefly review some available information on the relative cost of fresh vs. saline water cooling systems.

5.1. General cost factors

The comparative cost analysis was approached in two steps. First, "base case" costs were estimated for fresh water cooing towers. Second, cost factors or ratios were developed to scale from base case costs to an estimated of salt water tower costs.

5.1.1. Base case costs

The base case costs for fresh water towers were based on recent (2008) information obtained from major cooing tower vendors for a single set of design specifications; specifically,

- Water flow rate, L: 263,000 gpm
- Hot water temperature, T_h: 97 F
- Cold water temperature, T_c: 78 F
- Wet bulb temperature, T_{wb}: 70 F

This corresponds approximately to the heat load of a 500 MW steam plant. The power cost factor used in the determination of the evaluated cost case was assumed to be $3,200/HP. The base designs and costs are displayed in Table 5-1.

Table 5-1: Tower Design Configurations and Base Costs

Fresh Water Tower FRP, galvanized hardware	No. of Cells	Cell Width	Cell Length	Fan HP	Fan Dia	Base Cost
	#	ft.	ft.	HP	ft.	$ (000's)
Low First Cost Design	18	45	49	247	28	5,636
Evaluated Cost Design	15	67	60	131	32.8	7,062

5.1.2. Adjustment for saline make-up

The adjustment of the costs from fresh water to salt water towers is based on two separate sources of information. The first is a study conducted by Washington Group International in late 2001 (WGI, 2001)

to estimate the cost of retrofitting plants with once-through cooling to closed-cycle cooling with mechanical draft cooling towers. Both fresh and saline water installations were considered.

The cost estimates developed in this study included the entire cooling system with the exception of the condenser which was assumed to be retained in the retrofit. The system components for which a cost differential was identified were

- Cooling tower
- Circulating water pumps
- Make-up water pump
- Make-up "system"

As noted above, the use of saline make-up results in a larger tower, made more so by the use of low clog fill, which is also constructed of more costly materials. In the WGI study, the precise composition of the saline make-up water was not specified. However, it was stated that the saline water towers were operated at 2 cycles of concentration (as opposed to 5 cycles of concentration for the fresh water towers). Assuming standard sea water as make-up, this gives a circulating water salinity of approximately 70,000 mgl.

The analysis began by setting the freshwater tower conditions at WBT = 80, a 1 F recirculation allowance giving an inlet wet bulb of 81 F, an approach of 7 F, a range of 12 F and a condenser terminal temperature difference of 8 F. This corresponds to a condensing temperature of 108 F and a turbine exhaust pressure of 2.5 in Hga. It was not specified how the size and cost of the baseline freshwater tower designed to meet this performance was determined other than to say that

→ "structure costs assume a fiberglass mechanical draft tower with standard noise and drift abatement and no plume abatement" and

→ "costs were estimated by scaling cooling tower costs provided by cooling tower vendors for fresh water make-up cooling towers".

It was not stated whether the baseline costs were consistent with "low first cost" designs or "total evaluated cost" designs. However, as will be seen in a case study discussed below the cost ratio is essentially identical for both assumptions.

The salt water tower costs were adjusted in two ways: first, by adjusting the size of the tower to account for the performance reduction caused by the circulating water properties using the saltwater correction factor discussed in Section 3 (Figure 3.1); second, by increasing the cost of the tower to account for the more costly materials of construction

The adjustment in tower size was set at 1.07 which, for seawater at 2 cycles of concentration, is consistent with the "2x seawater" curve in Figure 3-2 for an L/G = 1. Although WGI did not specify the L/G, this would be in a reasonable design range as discussed in Chapter 2.

The adjustment in tower materials cost was set at x 1.4. This gives an overall cost ratio between saline and fresh water towers of x 1.5 (~ 1.07 x 1.4). (NB: It should be noted that while this procedure and the values used were clearly described in the text of (WGI, 2001), there was an apparent error in the report tables which caused the reported costs to differ in some cases from those that this procedure would yield.)

The second source of information was a estimate provided by former and current representatives of a cooling tower vendor (Wilber, K., 2004) for a given set of design specifications.

These were:

- → Water flow rate, L: 100,000 gpm
- → Hot water temperature, T_h: 120 F
- → Cold water temperature, T_c: 90 F
- → Wet bulb temperature, T_{wb}: 75 F

This corresponds approximately to the heat load of a 300 MW steam plant.

A comparison was provided between a fresh water tower and a tower operating with seawater as make-up and at 1.5 cycles of concentration, resulting in a circulating water salinity of 54,000 ppm. The two cases considered were a "low first cost tower" and an "evaluated tower". The evaluated tower is larger with a higher capital cost but uses less pump and fan power. The capital costs and the operating costs are balanced to arrive at an optimized lifetime cost. In this example, the current value of power was set at $100/HP for the pump and fan power. Table 5-2 shows the design configuration for towers of both low first cost and evaluated cost designs sized to account for the performance difference between fresh and brackish water at 54,000 ppm.

Table 5-2: Effect of source water quality on cooling tower design

Low Cost Design	No. of Cells	Cell Width	Cell Length	Fill Depth	Inlet Air Height	Fan HP	Fan Dia
	#	ft.	ft.	ft.	ft.	HP	ft.
Fresh Water Tower Douglas fir, galvanized hardware	8	36	42	5	12	200	28
Brackish Water Tower, 54000 ppm	8	42	42	4	13	200	28
Evaluated Cost Design	**No. of Cells**	**Cell Width**	**Cell Length**	**Fill Depth**	**Inlet Air Height**	**Fan HP**	**Fan Dia**
	#	ft.	ft.	ft.	ft.	HP	ft.
Fresh Water Tower Douglas fir, galvanized hardware	8	42	54	5.5	9	100	28
Brackish Water Tower, 54000 ppm	9	42	54	4	13	200	30

Again, the cost increase consisted of two parts---an adjustment to account for the reduced thermal performance and another for the more costly materials of construction. Table 5-3 shows the cost differentials attributable to the reduced performance.

Table 5-3: Cost Impact of Thermal Performance Reduction

Make-up Water	Low First Cost		Evaluated Cost	
	Cost ($1,000)	Impact (%)	Cost ($1,000)	Impact (%)
Fresh water	1,100	Base	1,400	Base
Brackish (54,000 ppm)	1,149.5	4.5%	1,498	7.0%

These fresh water costs are consistent with costs which were current in 2003 and are not directly comparable with the more recent (2008) costs displayed in Table 5-1. The ratios between the "Low First Cost" and "Minimum Evaluated Cost" are essentially the same (~ 1.25) in both cases.

Reference to Figure 3-2 indicates that a correction factor of 1.045 would be consistent with the Marley estimates for L/G's in the range of 1. to 1.5. The higher correction factor for the evaluated cost tower suggests that larger plan area per cell and an additional cell (in the case of the evaluated cost, brackish water tower) resulted in a higher air flow and hence a lower L/G in spite of the presumably lower fan/pump power for the evaluated cost design. While this cannot be confirmed with the information provided, a correction factor of 1.07 is consistent with an L/G of 0.5 or less.

The additional cost for the more costly materials to provide the corrosion resistance required for salt water operation is shown in Table 5-4. The comparison is between a "conventional" fresh water tower constructed of Douglas fir with galvanized fittings and an FRP tower with silicon bronze hardware and epoxy coating.

Table 5-4: Tower Cost Comparisons

Item	Low First Cost		Evaluated Cost	
	Douglas Fir	FRP	Douglas Fir	FRP
"Base Tower"	1,100	1,287	1,400	1638
Increase for salinity	--	58	--	115
Silicon Bronze fittings	--	112	--	120
Epoxy coatings	--	28	--	30
Total	1,100	1,485		1,903
% increase	--	35%		36%

Several points are noteworthy.

1. There is good consistency among the several sources of information.
    a. The case study (Wilber, K., 2004) and the generalized cost factor analysis (WGI, 2001), are roughly consistent and suggest a range of 35% to 50% increase in cost for salt or brackish water towers compared to fresh water towers.
    b. The difference in the two estimates is primarily in the differential costs of materials rather than the cost differences attributable to performance reduction. This may be due, in part, to the fact that the two estimates were done at different times; 2001, in the case of the WGI report and 2004 for the case study. Significant variations in the costs of lumber, plastics, and high grade metal parts have occurred over the past few years which may have altered the cost ratios. In any case, the determination of a 35% to 50% range is considered adequate for a general survey of this type.
    c. The ratio between the "Low First Cost" estimate and the "Minimum Evaluated Cost" estimate is consistent between the 2003 and the 2008 estimates.
2. Care must be taken in applying the correction factors from the two earlier sources to the more recent base costs. In the earlier studies, the base, fresh water case was taken to be a wood tower using Douglas Fir. Part of the cost increase in gong to salt water towers was due to the fact that the salt water towers were assumed to be FRP construction. In the 2008 costs, the base case is already FROP construction, so that portion of the cost increase cannot be applied to the base figure.
3. Therefore, a reasonable estimate of the increase in cooing tower costs is includes the factor of 1.045 to 1.07 due to performance factors and a reduced portion of the materials factor resulting in an increase of approximately 15%.

4. The cost analyses discussed above included only the cooling tower itself. Other components of wet recirculating systems are also affected by make-up water salinity as noted in Section 5.1. Table 5-5 lists the cost ratios for other major components used in the WGI study. While the cooling tower is typically the largest cost component of the system, these differences can be sizable for large installations. Again, the absolute cost values are consistent with 2001 costs and have not been scaled to 2008 costs, but the cost ratios are assumed to be appropriate.

Table 5-5: Cooling System Component Cost Comparisons (from (WGI, 2001))

Item	Fresh water	Salt water	Cost ratio
Cooling tower	$24/TU	$33.6/TU	1.4
Circ. water pump	$130 - $260/BHP	$210 - $416/BHP	1.6
Make-up water pump	$337/BHP	$539/BHP	1.6
Make-up system	$150/gpm	$200/gpm	1.3

6.0 Summary and Conclusions

The use of seawater, brackish estuarine or ground water, or high-salinity reclaimed water for cooling tower makeup is an attractive alternative to the use of freshwater in some locations. Table 2-1 lists over 50 seawater or brackish water towers currently installed in the United States, and over 90 worldwide. This section reviews the effect of using non-freshwater as cooling tower makeup on thermal performance, cost, environmental impact and operation and maintenance.

6.1. Effect on Thermal Performance

Several of the thermophysical properties of high-salinity water differ from those of freshwater. These include the following:

- Density
- Specific heat
- Surface tension
- Thermal conductivity
- Vapor pressure
- Viscosity

Of these, the most important in its effect on cooling tower performance is vapor pressure. The volumetric heat capacity (the product of density multiplied by specific heat) can affect the optimum design and operating point. Thermal conductivity, viscosity, and surface tension play minor roles in the thermal performance of cooling towers; surface tension can affect the effectiveness of drift eliminators.

The presence of salts in water reduces the vapor pressure at any given temperature, as seen in Figure A.2 in Appendix A. This reduces the driving force for evaporation and the accompanying latent heat transport. Therefore, a higher fill volume or fill transfer coefficient will be required to transfer the same amount of heat, requiring a larger and more costly cooling tower. Alternatively, a tower of the same size and fill configuration will cool less water to the desired cold water temperature or deliver a higher cold water temperature.

For circulating water salinities, given by the salinity of the makeup water multiplied by the tower cycles of concentration, of x 1.5 to x 2 that of seawater (~50,000 to 70,000 ppm), the thermal capability of a high-salinity tower will be reduced by 4% to 8% below that of a freshwater tower at the same operating conditions. A recommended rule-of-thumb for specifying towers is to increase the design ambient wet bulb temperature by 0.055°C (0.1°F) for each 4000 ppm of circulating water salinity.

6.2. Effect on Cooling System Cost

In comparison to cooling systems designed to operate on freshwater, salt or brackish water systems are more expensive. This is the result of several factors.

- The properties of seawater lead to reduced thermal capability, requiring a larger and more expensive tower.
- The higher levels of dissolved and suspended solids in salt or brackish water sources may require the use of lower efficiency, "low-clog" fill, again requiring a larger tower.
- The aggressive nature of the higher salinity water normally requires the use of more corrosion-resistant, more expensive materials for cooling system components and hardware.
- Under some circumstances, deterioration of tower or basin materials may occur, resulting in costly maintenance or repair.
- The effects of salt drift deposition may result in higher costs for cleaning, protection, or repair of equipment, structures, and surfaces in the vicinity of the tower.

Cost estimates were obtained from a study by an experienced architecture and engineering firm using generalized cost adjustment factors, and from a case study for a particular set of design specifications.

1. The case study and the generalized cost factor analysis are roughly consistent and suggest a 35% to 50% increase in cost for salt or brackish water towers compared to freshwater towers.
2. The difference in the two estimates is primarily in the differential costs of materials rather than the cost differences attributable to performance reduction. This may be due, in part, to the fact that the two estimates were done at different times, nearly three years apart.
3. The differential cost estimates apply only to the cooling tower itself. Other components of wet recirculating systems also are affected by makeup water salinity.

6.3. Environmental Impacts

A number of environmental effects studies have been conducted by comparing deposition rates on surrounding land before and after the installation and operation of salt or brackish water cooling towers.

All studies reach essentially similar conclusions: that no significant increase in salt concentrations in soils or vegetation, nor any symptoms of environmental injury, were observed in the vicinity of the plants.

6.4. Effect on Operation and Maintenance

Plant visits were made to four plants, and telephone interviews were held with two additional plants and one cooling tower vendor.

The major conclusions obtained from these visits and interviews are as follows:

1. Recent installations of mechanical-draft cooling towers operating on high-salinity makeup water using fiberglass reinforced plastic (FRP) structure, polyvinyl chloride

(PVC) fill and corrosion-resistant fittings (high-grade stainless steel, silicon bronze [coated], titanium) have operated satisfactorily, with no extraordinary O&M problems.

2. Operating results have been excellent but long term experience (> 15 years) is lacking.
3. Nearly all plants with high-salinity cooling towers, both natural and mechanical draft, have encountered accelerated corrosion on unprotected metal surfaces on buildings and equipment at the plant site near the towers.
4. Both mechanical and natural-draft tower structures and basins constructed of concrete have experienced varying degrees of deterioration from exposure to salt water.

7.0 References

Aull, R. 2005. Personal Communication.

Boyce, S. G. 1954. The Salt Spray Community.

California Coastal Commission. 1993. Seawater Desalination in California--Key Desalination Facts.

Concrete Construction magazine, Repair Agent Stabilizes Concrete Structures," November 1, 2006. http://www.concreteconstruction.net/industry-news.asp?sectionID=707&articleID=388249.

CTI. 2005. CTI ToolKit, Version 3.0b. Cooling Technology Institute.

Davis, E. A. 1979. Environmental Assessment of Chalk Point Cooling Tower Drift and Vapor Emissions. Johns Hopkins University, PPSP-CCCTP-28.

DiFilippo, M. 2003. Use of Degraded Water Sources as Cooling Water in Power Plants. EPRI and California Energy Commission. 1005359.

Eftekharzadeh, S., M. Baasiri, and P. Lindahl. 2003. Feasibility of Seawater Cooling Towers for Large-Scale Petrochemical Development. Cooling Technology Institute. TP03-17.

Fluor R/D Division. 1957. Impact of Salinity on Corrosion. Fluor Corporation.

Merkel, F., "Verduftungkuhlung," Forschungarbeiten No. 275, 1925.

Micheletti, Wayne. 2006. "Atmospheric Emissions from Power Plant Cooling Towers." *Powerplant Chemistry* 8(3): 141–153.

Mitchell, Robert D. 1989. Survey of Water-Conserving Heat Rejection Systems. EPRI. EPRI GS-6252.

Office of Saline Water 1959. "Normal" Seawater Chemistry. U.S. Department of the Interior.

Perry, R. H., D. W. Green, Perry's Chemical Engineer's Handbook, 7th Edition, 1997

PG&E. 1979. Assessment of Vegetation Stress and Damage Near the Geysers Geothermal Power Plant Units. Pacific Gas & Electric Co.

Porter et al. 2000. Vertical and Horizontal Aerosol Scattering Fields over Bellows Beach, Oahu During SEAS Experiment. School of Ocean and Earth Science, University of Hawaii.

Reisman, J., and G. Frisbie. 2002. Calculating Realistic PM10 Emissions from Cooling Towers.

Rossnecht, G. F., W.P. Elliott, and F.L. Ramsey. 1973. "The Size Distribution and Inland Penetration of Sea Salt Particles." *Journal of Applied Meteorology* 12(5): 825–830.

Saline Water Conversion Engineering Data Book, 2nd Edition, Department of Interior, Office of Saline Water, November 1971 (Author was M. W. Kellogg Company)

Shofner, F. M., et al. 1973. Ambient Sea Salt Measurements in the Forked River, NJ Environs.

South Coast Air Quality Management District (SCAQMD), Minutes of Board Meeting, June 3, 2005 (Available at www.aqmd.gov/hb/2005/050617a.html)

Ting, Bing-Yuan, and D. M. Suptic. 1991. The Use of Cooling Towers for Salt Water Heat Rejection. The Marley Cooling Tower Company.

U.S. Environmental Protection Agency. 1995. Compilation of Air Pollutant Emission Factors (AP-42; Section 13.4 --Wet Cooling Towers). Environmental Protection Agency.

U.S. Environmental Protection Agency. 2000. 316(b) Phase II Technical Development Document, Chapter 6, Environmental Protection Agency.

U.S. Environmental Protection Agency. 2006. National Ambient Air Quality Standards (NAAQS).

WGI. 2001. Estimated Cost of Compliance with EPA Proposed Rule 316(b). Washington Group International. Project 25258.

Wilber, K. R. 1974. An Experimental Approach to the Evaluation of the Collection Efficiencies of Meshes Using the Mechanism of Inertial Impaction. University of Tennessee.

Wilber, K. R. 1975. Ambient salt concentration study for Atlantic City Electric Company, B. L. England Station.

Wilber, K. R., and R. O. Webb. 1983. Environmental Effects of Cooling Towers. Atomic Industrial Forum.

Wilber, K. 2004. Personal Communication.

Woodcock, A. H. Atmospheric Salt Particles and Raindrops. 1952.

Woodcock, A. H. 1953. Salt Nuclei in the Marine Air as a Function of Altitude and Wind Force.

Appendix A

Properties of Seawater

Seawater Composition

(Information in Appendix A obtained from Perry (1997) and Saline Water Conversion Engineering Data Book (1971)

Table A-1. Composition of "Normal" Seawater

"Normal" Seawater Chemistry (1)		
US Department of Interior, Office of Saline Water, July 1959		
Na	10,556	mg/kg (2)
K	380	mg/kg
Ca	400	mg/kg
Mg	1,272	mg/kg
HCO_3	140	mg/kg
Cl	18,980	mg/kg
Br	65	mg/kg
SO_4	2,649	mg/kg
SiO_2	<10	mg/kg
Other	31	mg/kg
Total	**34,483**	**mg/kg**

Notes.....

1. Only major ions shown.
2. These are true "ppm" units and are approximately the same as mg/l.

Vapor Pressure

Correlating Equations for Vapor Pressure

Freshwater

$$p = 8.0439E\text{-}09T4 - 6.5750E\text{-}07T3 + 8.5848E\text{-}05T2 - 1.0248E\text{-}03T + 4.6622E\text{-}02$$

Seawater (TDS ~ 35,000)

$$p = 1.0511E\text{-}08\ T^4 - 1.7569E\text{-}06\ T^3 + 2.3539E\text{-}04\ T^2 - 9.1406E\text{-}03T + 1.9585E\text{-}01$$

2x Seawater (TDS ~ 70,000)

$$p = 3.9773E\text{-}09\ T^4 - 2.1465E\text{-}08\ T^3 + 6.6345E\text{-}05\ T^2 - 2.1540E\text{-}03T + 8.8876E\text{-}02$$

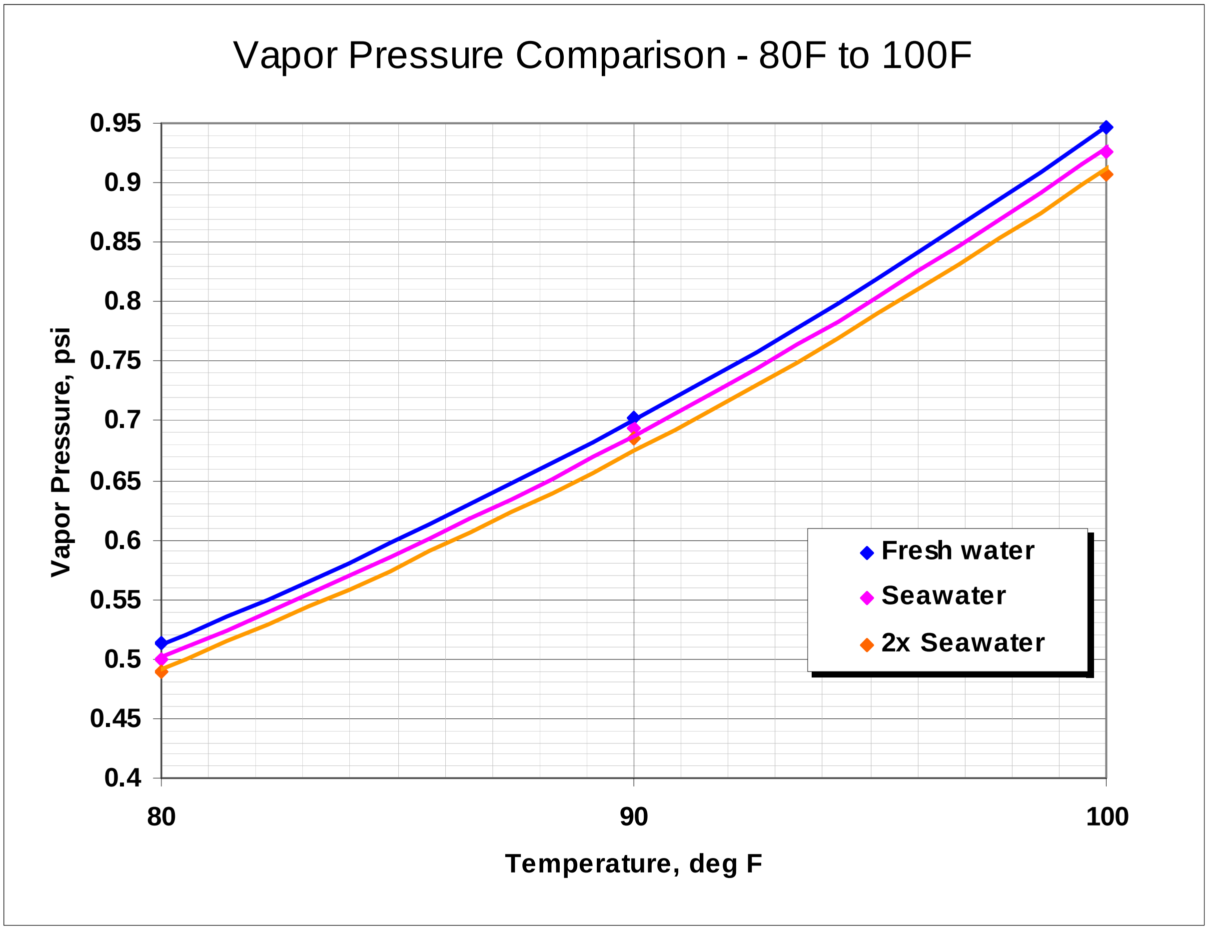

Figure A-2a. Vapor pressure (80° to 100°F)

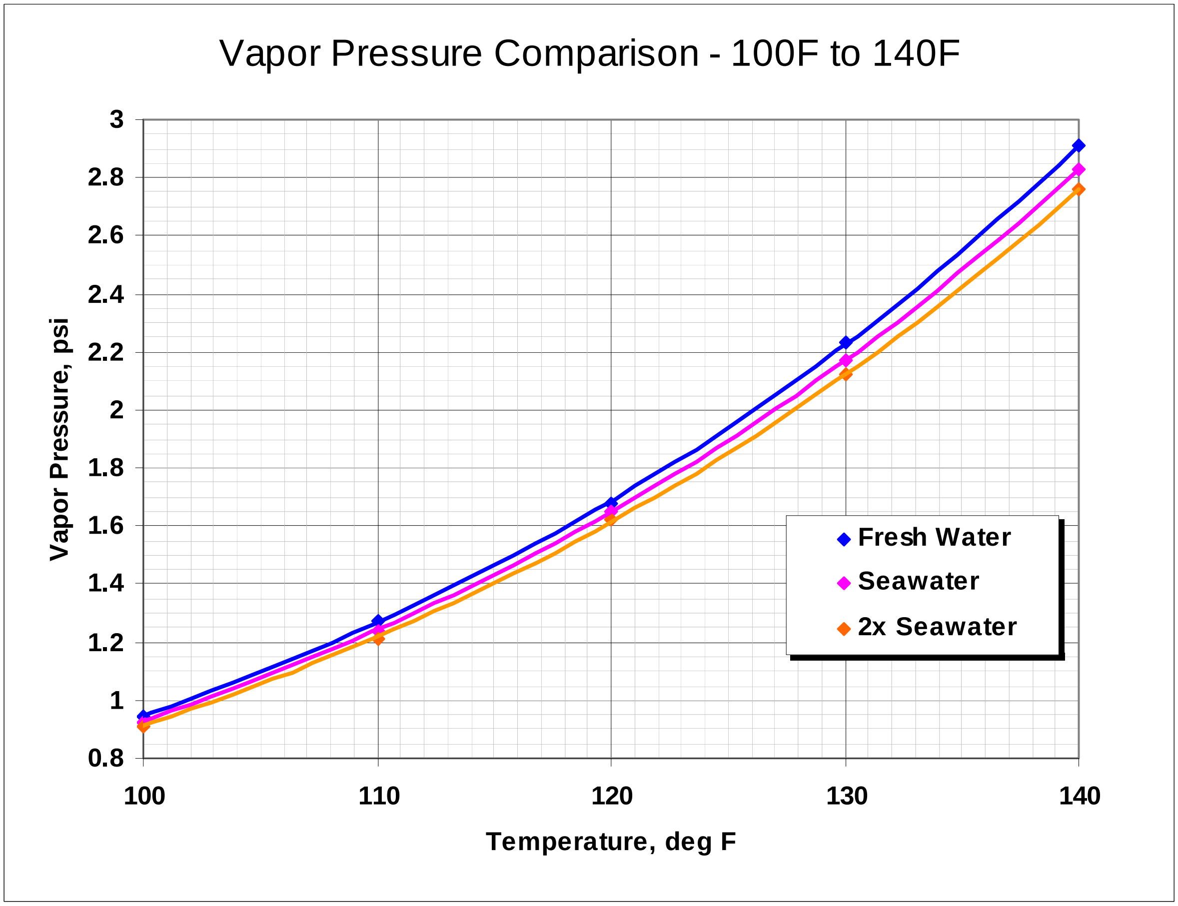

Figure A-2b. Vapor pressure (100° to 140°F)

Surface Tension

Correlating Equations for Surface Tension

Freshwater

$$\sigma = -6.2500E\text{-}05T2 - 7.7607E\text{-}02T + 7.8297E\text{+}01$$

Seawater (TDS ~ 35,000)

$$\sigma = -8.0357E\text{-}05T2 - 7.4107E\text{-}02T + 7.8914E\text{+}01$$

2x Seawater (TDS ~ 70,000)

$$\sigma = -4.4643E\text{-}05T2 - 8.0679E\text{-}02T + 7.9991E\text{+}01$$

Figure A-3. Surface tension (40° to 140°F)

Viscosity

Correlating Equations for Viscosity

<u>Freshwater</u>

$$\mu = 1.3063E\text{-}04T^2 - 4.4363E\text{-}02T + 4.7808$$

<u>Seawater (TDS ~ 35,000)</u>

$$\mu = 1.3688E\text{-}04\ T^2 - 4.6918E\text{-}02T + 5.1116$$

<u>2x Seawater (TDS ~ 70,000)</u>

$$\mu = 1.4313E\text{-}04\ T^2 - 4.9283E\text{-}02T + 5.4285$$

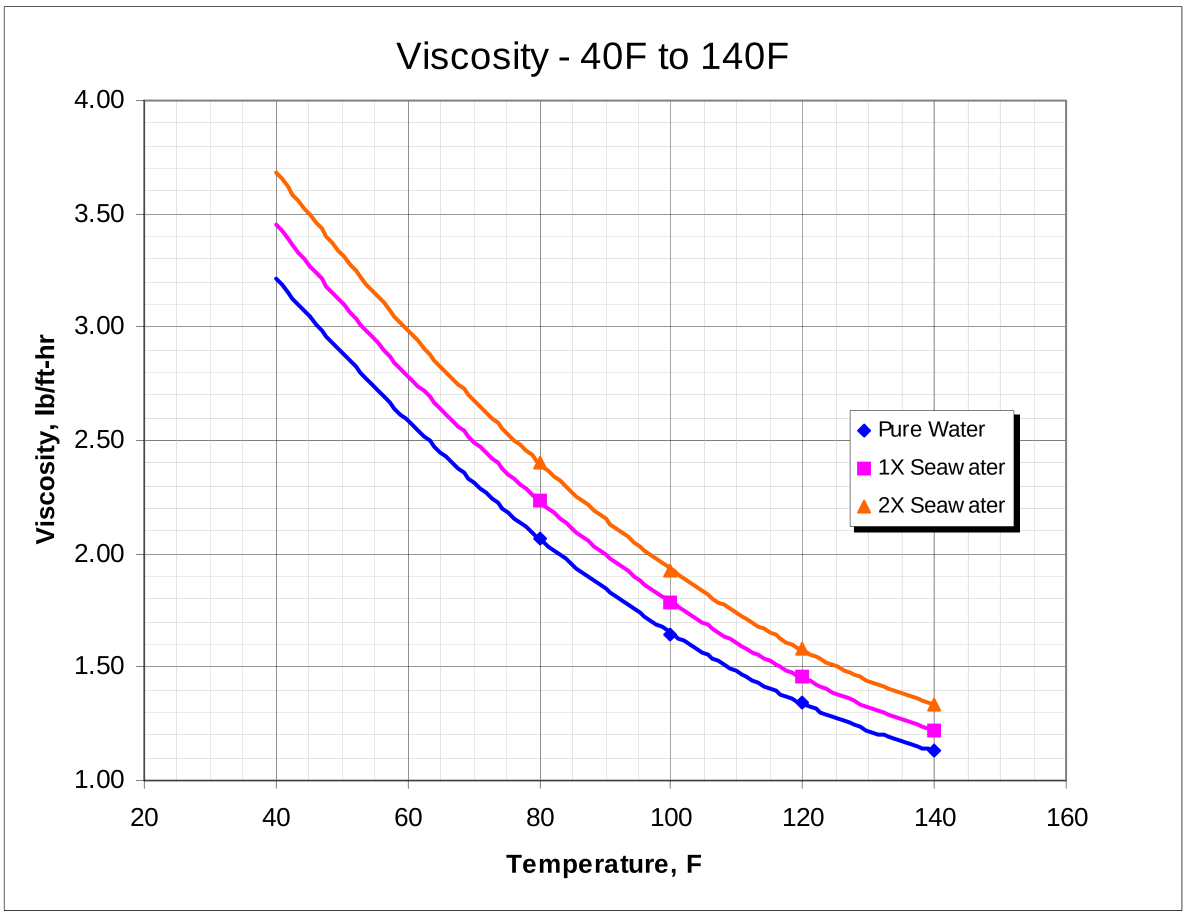

Figure A-4. Dynamic viscosity (40° to 140°F)

Thermal Conductivity

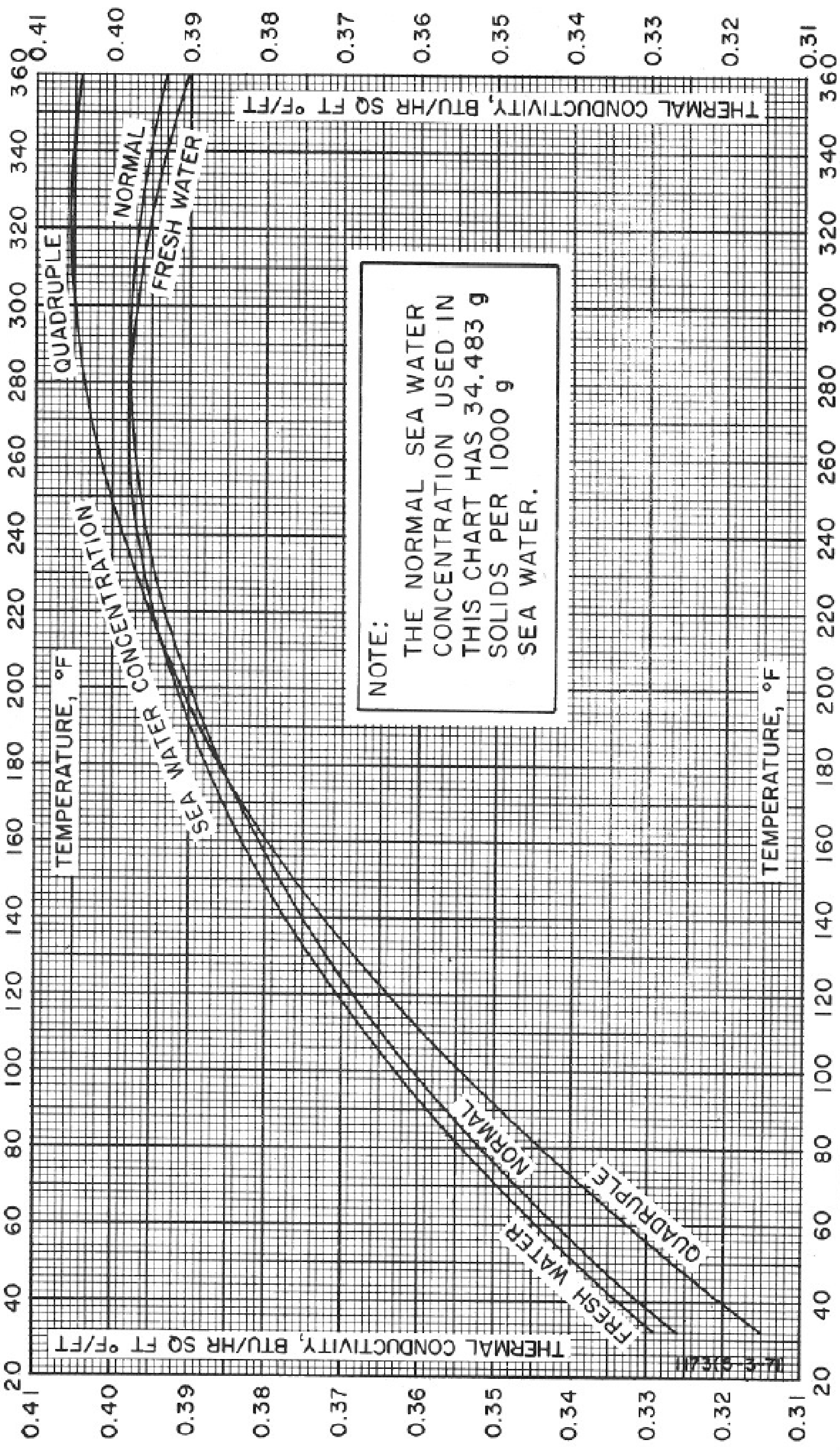

Figure A-5. Thermal conductivity (Source: M.W. Kellogg Company, *Saline Water Conversion Engineering Data Book,* 2nd Edition, Department of Interior, Office of Saline Water, November 1971)

Density

Correlating Equations for Density

Freshwater

$$\varrho = -2.1661E\text{-}08T^3 - 7.7583E\text{-}06T^2 + 6.7946E\text{-}04T + 8.3283$$

Seawater (TDS ~ 35,000)

$$\varrho = -4.4870E\text{-}08\ T^3 + 1.1936E\text{-}06\ T^2 - 4.8336E\text{-}04T + 8.5780$$

2x Seawater (TDS ~ 70,000)

$$\varrho = -4.6417E\text{-}08\ T^3 + 3.9388E\text{-}06\ T^2 - 1.1106E\text{-}03T + 8.8145$$

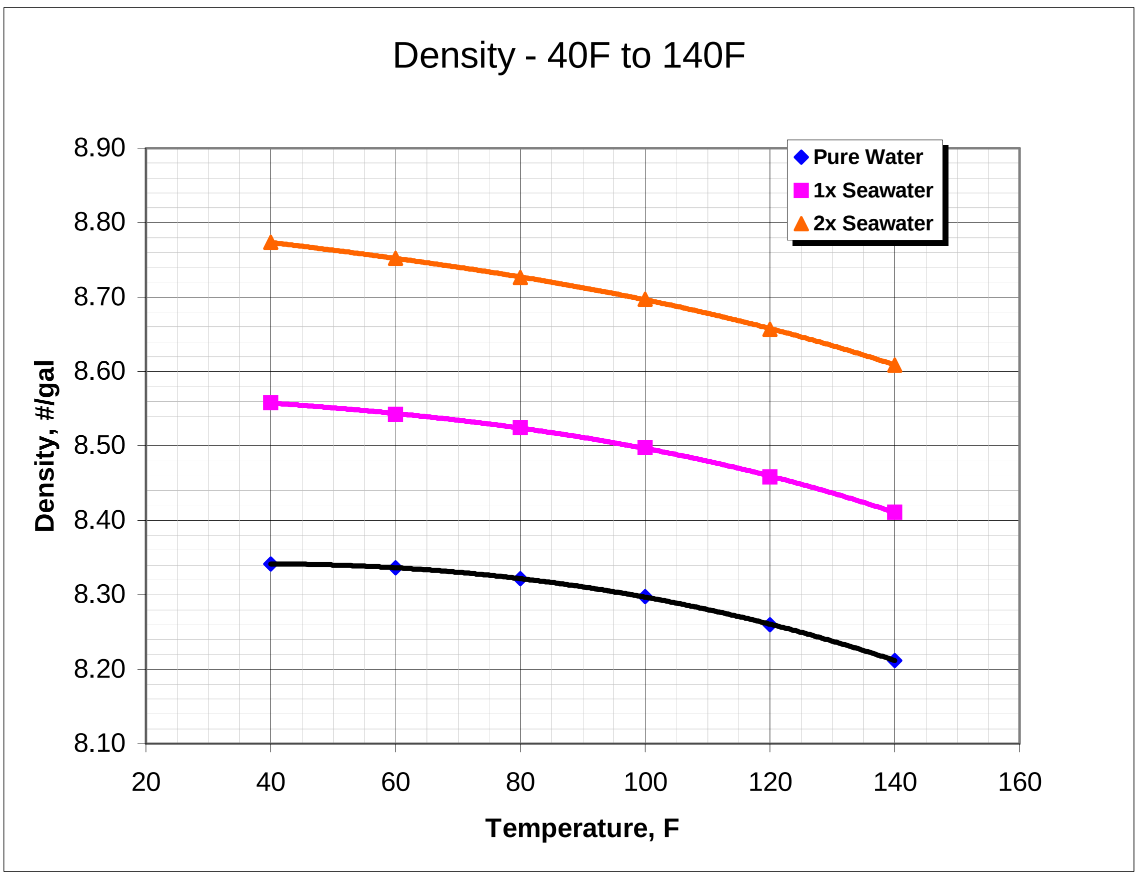

Figure A-6. Density (40° to 140°F)

Specific Heat

Correlating Equations for Specific Heat

Freshwater

c_p = 1.6927E-10T^4 - 7.2627E-08T^3 + 1.2276E-05T^2 - 9.5425E-04T + 1.0269

Seawater (TDS ~ 35,000)

c_p = 1.3021E-11 T^4 - 4.5718E-09 T^3 + 6.5104E-07T^2+ 1.5847E-05T + 9.5287E-01

2x Seawater (TDS ~ 70,000)

c_p = 3.7037E-09 T^3 - 1.4196E-06 T^2 + 2.7834E-04T + 9.0270E-01

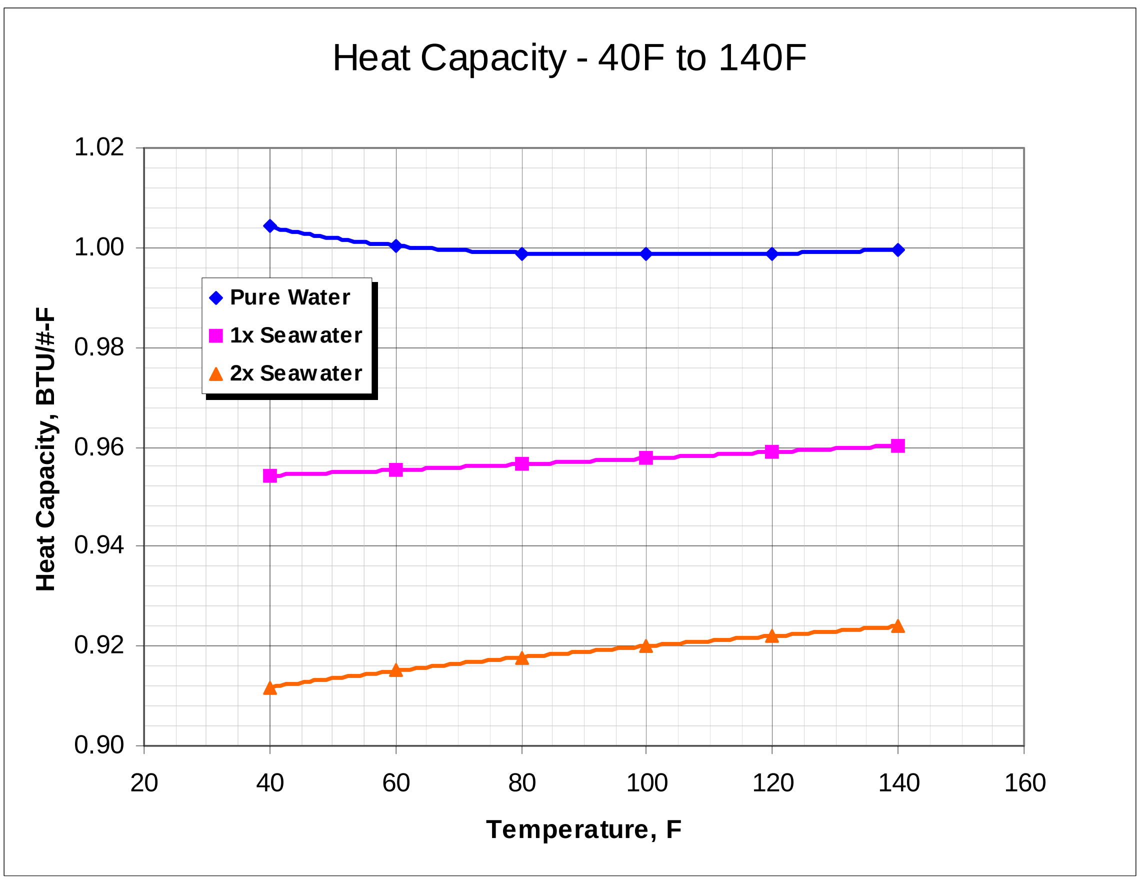

Figure A-7. Comparison of specific heat (from Perry's *Chemical Engineer's Handbook,* 7th edition, 1997)

Appendix B

Derivation of Cooling Tower Performance Characteristics

Tower Performance Characteristics

The cooling of the water is achieved through the combined processes of heat and mass transfer from the hot water to the air as they pass through the tower fill. A brief description of the process will assist in understanding how the properties of the water, and, in particular, how the differences between the thermo-physical properties of salt or brackish water and those of freshwater affect cooling tower performance.

As indicated in Figure B-1, the hot water enters the tower at the top and falls under gravity down through the tower fill and into the cold water basin. The air is drawn into the tower at the bottom and flows upward, counter to the downflow of the water, and exits through the fan to the atmosphere.

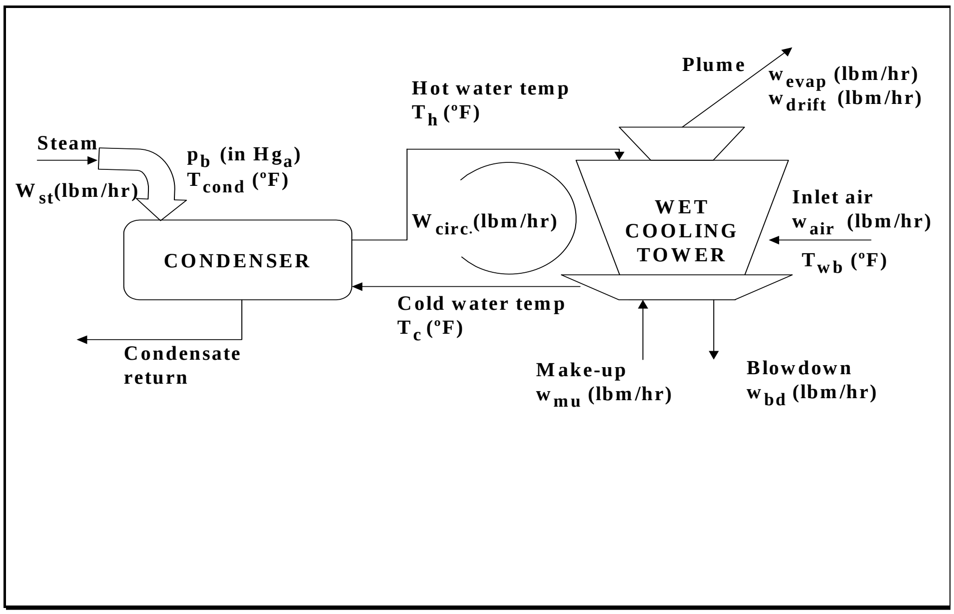

Figure B-1. Closed-cycle cooling system mass and heat balance

The purpose of the fill is both to slow the water as it descends through the fill and to create a large interfacial area between the water and the air, providing more time and a larger area for the transfer processes to take place. Fills are of two general types: film fill and splash fill. The film fills cause the water to flow in narrow films on the fill surfaces. The fill geometry is designed to and by geometric disrupt and mix the films by causing them to turn or reform as they flow downwards. Splash fills create small droplets as the falling water impacts the fill surfaces, creating fresh surface for heat and mass transfer.

Determination of the tower performance characteristics required for a given cooling load proceeds as follows:

The heat load which must be rejected by the cooling tower to cool a given water flow, L, from the hot water temperature, T_h, to the desired cold water temperature, T_c, is given by

$$Q_w = L * c_p * (T_h - T_c) \qquad \text{(Eq. B-1)}$$

The heat transferred to the air equals that from the water and is given by

$$Q_a = G * (h_{airex} - h_{airamb}) \qquad \text{(Eq. B-2)}$$

where

G = air flow rate (lb/hr)

h = enthalpy of air stream per lb of dry air (Btu/lb)

The transfer of heat from the water to the air stream at each point on the air-water interface within the tower is made up of

- A sensible heat component, driven by the difference between the local water surface temperature and the local free stream air temperature.
- A latent heat component, carried by a mass transfer of evaporating water driven by the difference between the vapor pressure of water at the local water temperature and the vapor pressure of the water vapor in the air stream.

Several critical assumptions simplify the analysis:

1. The water film is well mixed so the water surface temperature is the same as the bulk water temperature.
2. The air at the surface of the film is saturated at the water temperature.
3. The physics of the heat and mass diffusion processes are essentially the same; i.e., the Lewis number is equal to 1.

With these assumptions, the total heat transfer per unit interfacial area can be accurately represented with a combined transfer coefficient, K, and the difference between the enthalpy of air saturated at the local water temperature and the enthalpy of the bulk air stream.

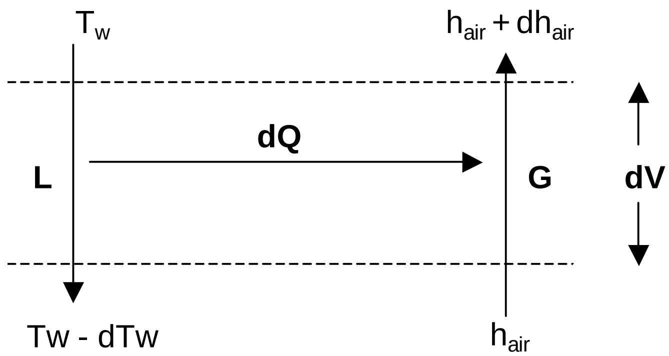

Figure B-2. Incremental Heat Transfer Analysis

From Eq. (B-1) and Figure B-2,

$$KadV(h_{sat\,@\,Tw} - h_{air}) = LdT_w \qquad \text{(Eq. B-3)}$$

Integrating across the fill volume from 0 to V, yields

$$KaV/L = \int_{T_c}^{T_h} \frac{dT_w}{h_{sat\,@\,T_w} - h_{air}} \qquad \text{(Eq. B-4)}$$

The integration can be understood graphically in Figure B-3.

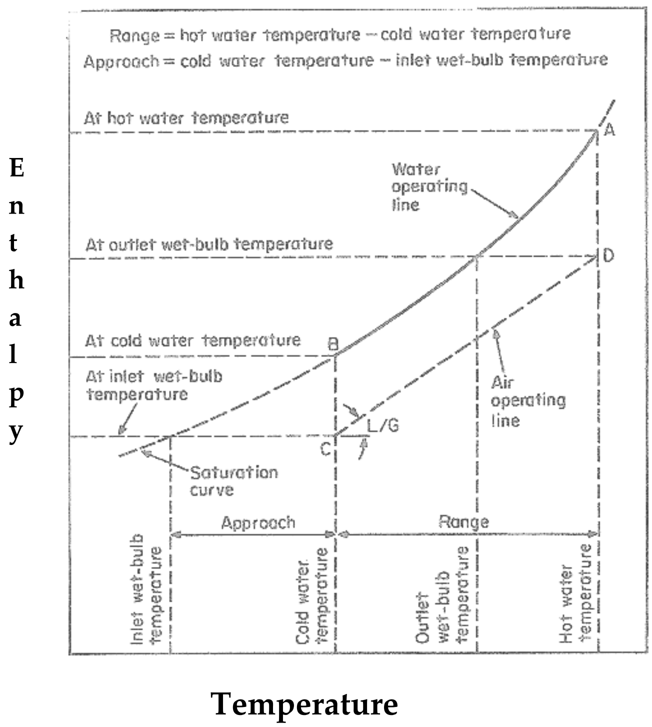

Figure B-3. Cooling tower operating curves

The driving force for the combined heat transfer is the distance from the line A-B which represents the water operating line between T_h and T_c and also the enthalpy of saturated moist air. The line C-D represents the air operating line running from an inlet enthalpy consistent with the ambient wet bulb temperature and increasing linearly with a slope of L/G to an exit enthalpy consistent with the overall heat balance.

Since the enthalpy of moist air is essentially a function only of the wet bulb temperature independent of relative humidity, it is not possible from the foregoing analysis to determine the exit state of the air. A further assumption by Merkel (1925) states that the exit air is saturated at the prescribed exit enthalpy and corresponds to some temperature intermediate between the water hot and cold temperatures:

$$h_{ex} = h_{amb} + L/G * (T_h - T_c) \qquad \text{(Eq. B-5)}$$

This suffices to specify the complete state of the exit air and to determine the evaporation rate from the cooling tower from

$$w_{evap} = G * (W_{ex} - W_{amb}) \qquad \text{(Eq. B-6)}$$

where

$$W = \text{specific humidity in lb moisture/lb of dry air}$$

Based on the foregoing analysis, knowing the ambient wet bulb and the inlet and outlet water temperature is sufficient to determine the required tower characteristic (KaV/L). This value is readily generated by programs such as the CTI Toolkit. A sample set of curves for a given wet bulb and a given range is shown in Figure B-4 for a number of approach temperatures as KaV/L vs. L/G.

The performance characteristics of many fills can be approximated by a polynomial expression of the form

$$KaV/L = C * (L/G)^n \qquad \text{(Eq. B-7)}$$

Figure B-4 shows such a fill characteristic with nominal values of n = -0.7 and C = 1.5 superimposed on the performance curves of a tower with a 32.4°F range at an 80°F wet bulb. The intersections of the characteristic line with the performance curves gives the approach temperature which can be obtained for the given range and wet bulb temperature for any L/G.

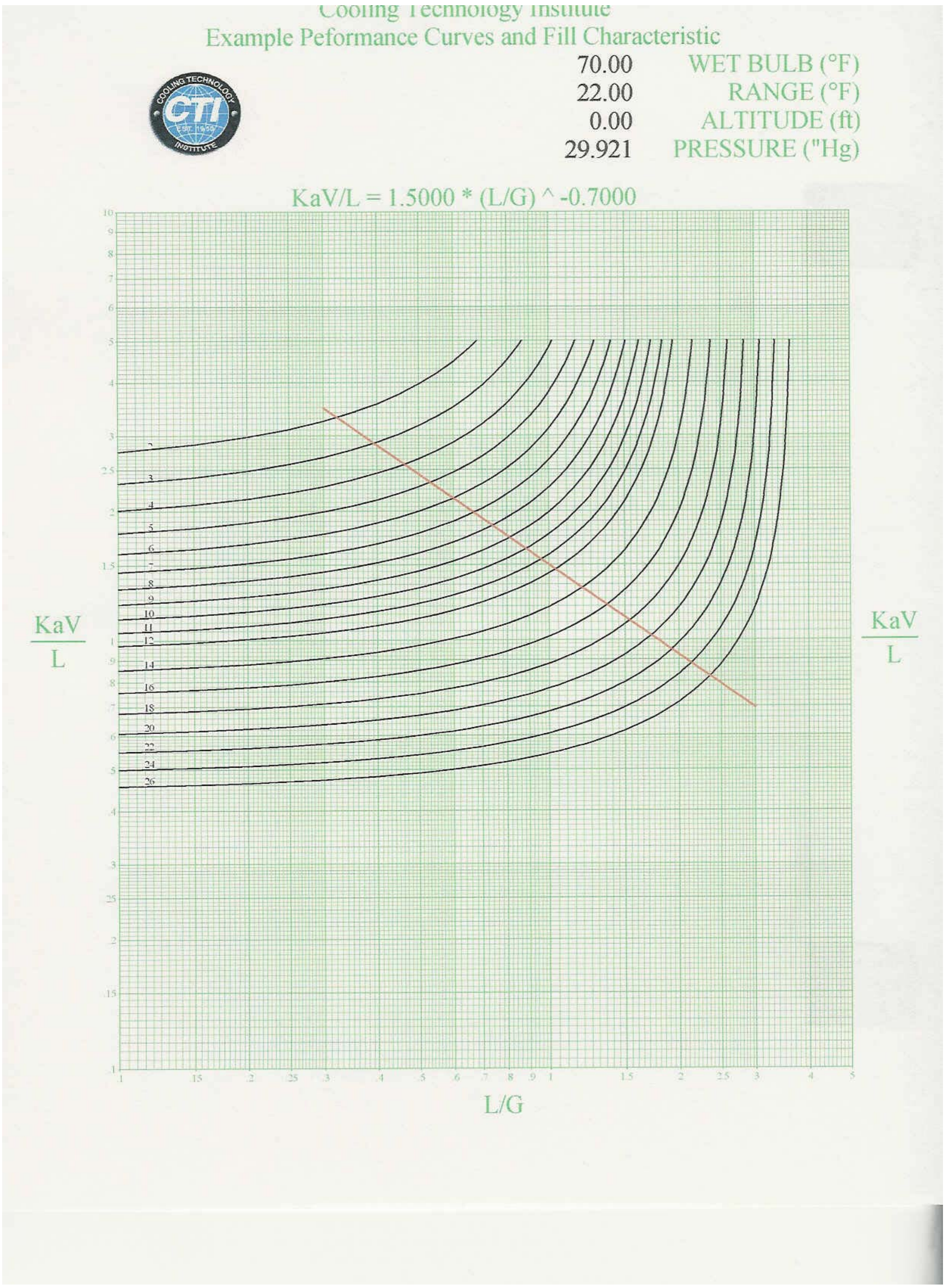

Figure B-4. Example performance curves and fill characteristics (from CTI Toolkit for specified range and wet bulb temperature)

Appendix C

Site Visit and Telephone Interview Reports

C.1 St. Johns River Power Park

The plant was visited on March 27, 2006.

Plant Location and Contacts

St. Johns River Power Park
11201 New Berlin Road
Jacksonville, FL 32226

Paul M. Smith
Plant Manager, StJRPP Tel:
904-665-8726
Fax: 904-665-8957
Cell: 228-591-8725
E-mail: smitpm@jea.com

John E. Reid
Superintendent Logistics, Proj/Contr & Bus. Admin.
Power Generation
Tel: 904-665-8952
Fax: 904-665-8800
Cell: 904-591-4242
E-mail: reidje@jea.com

Bruce Kofler
Environmental Manager
Tel: 904-665-7886
Fax: 904-665-8719
Cell: 904-591-4242
E-mail: koflbw@jea.com

Plant Description

The plant, jointly owned by JEA and Florida Power and Light, consists of two identical units. Each is rated at 624 MW and is fossil-fueled (2/3 Columbian coal/1/3 petroleum coke). Unit #1 began commercial operation in 1987; Unit #2, in 1988.

Cooling Towers

Each unit is equipped with a Custodis-Cottrell hyperbolic, natural-draft, counter-flow cooling tower as shown in Figure B.1-1. The towers are 462 feet high with a basin diameter of 338 feet.

Figure C.1-1. St. Johns River Power Park: Hyperbolic natural-draft towers

The design for each tower is:

- Circulating water flow: 247,700 gpm
- Hot water temperature: 114.5°F
- Cold water temperature: 90°F
- Design wet bulb: 80°F (@ 58% rh)

Source Water

The source of makeup water for the towers is on a back channel of the St. Johns River immediately adjacent to the discharge canal of the Northside Generation Station. The intake pumps supply makeup water through a 1.5-mile pipeline to the towers. The discharge temperature from the Northside condensers varies from about 91°F in the summer to 86.5° in the winter.

The water quality varies seasonally and is affected by rainfall, storms and dredging activity as well as river traffic. The conductivity varies from 7,895 (minimum) to 50,464 (maximum) with an average value of 33,862 over the period from 2001 to 2005.

Water Treatment

The towers are operated at < 1.5 cycles of concentration with continuous makeup and blowdown. The blowdown is discharged to the Northside Generating Station's cooling water discharge with no additional treatment.

No scaling or corrosion control is used. Biofouling is controlled with continuous chlorination to maintain <0.02 TRO (total residual oxidant) in the discharge.

Materials of Construction

Structure: Portland cement, Type II @ 4,000 psi

Columns: Portland cement, Type II @ 5,000 psi

Fill: PVC module SNCS-20PVC

Hangers and fittings: fiberglass (hangers, rods, and nuts)

Distribution piping/nozzles: PVC

Drift eliminators: PVC Type D-15

The tower's shell (veil) was constructed via the slip form method of material placement during original construction.

7.1.1. Cooling Tower Fill

Both towers were originally equipped with a low-fouling film fill. The towers met their performance guarantees and then operated satisfactorily for about 12 years before operating problems were noted.

Unit #1 was repacked with original equipment manufacture (OEM) fill in 2001, followed by the installation of new salt drift eliminators in 2003, and operation continues at a satisfactory level of performance.

Unit #2 was repacked in 2002 with a high-efficiency fill and new drift eliminators and nozzles. Fill plugging and solids buildup in the fill was noted during late 2005. New dry film packs weigh approximately 40 lb (depending on size). During a short notice outage, several packs were removed for fouling evaluation and the removed packs weighed over 200 lb. Although chlorination was supposed to prevent fouling and buildup of attached material, discharge constraints have impacted allowable chlorination levels which contributed to the fouling and plugging.

Drift

The towers were fitted with drift eliminators designed for a maximum drift loss of 0.002% of the circulating water flow rate (corresponding to approximately 5 gpm per unit) including "blow through" (from the "rainzone" above the basin underneath the fill) with 45-mph winds. Performance of the drift eliminators has been satisfactory. They have been replaced once during the life of each unit.

Environmental effects

A pre-/post-operational study was conducted to evaluate the effect of drift on salt concentrations in deposition, soil concentration, and vegetation uptake on and near the site. Four test plots were set up and monitored including a control site approximately 1.5 miles NNW of the cooling towers. Measurements were made over three time periods, specifically:

1. Prior to operation: 2/86 to 12/86
2. Unit #1 operating: 1/87 to 3/88
3. Both units operating: 4/88 to 9/89

The conclusions, documented in detail in permitting reports, are summarized as follows :

- Some increased NaCl concentration was found in deposition samples after Unit #2 began operation.
- No significant increases were seen in soil or vegetation samples.
- Vegetation at the site with the highest deposition was apparently unaffected.
- No injury symptoms related to NaCl were observed on pasture grass or other vegetation on or in the vicinity of the Power Park.

Maintenance effects

The primary effects of drift are found on-site in the form of extensive corrosion of metal roofs and unprotected metal surfaces (handrails, stairways, piping, gratings, etc.) throughout the plant. Surfaces have been cleaned, scraped and painted with corrosion resistant paint (NOXYDE—a highly impermeable European paint product) to resist the corrosive effects of the salt drift. This appears to have been successful where implemented.

Salt deposits on switchyard insulators have lead to arcing problems. These are minimized through the use of larger insulators and insulators made of polymer-based material or silicone-coated porcelain.

Concrete Deterioration

The most serious problems from the salt environment have related to the concrete structure of the cooling towers themselves. Significant concrete spalling and embedded steel (rebar) corrosion has been evident since the early 1990s. Examples on the tower shell and the support columns are shown in Figures B.1-2a and –2b.

Various approaches to halt the deterioration including coatings, epoxies, flame-sprayed zinc, and others have been tried. All provided some temporary benefit but none lasted. A more elaborate approach is now being taken.

For the flat shell surface, spalled concrete is removed as required (sometimes to the second layer of reinforcing rebar 6 inches in depth). Wire leads are placed at specific intervals on selected rebar in each area and new concrete is "shot" to the surface. A zinc mesh screen is placed over the freshly filled concrete area and the leads (from the rebar) are attached to the mesh. The mesh is covered with a final layer of concrete (~1 inch thick).

For columns and the lintel, spalled concrete is removed as well and leads are installed on the rebar. A prefabricated Fiberglass form containing a sheet of zinc mesh (suspended midway between the Fiberglass shell and the column surface by take-aways) is placed over the column. There is a specific form for the lintel as well. The leads are attached to the zinc mesh before the form is closed. Concrete is pumped into the forms by way of ports along its length. After filling, the ports are capped.

A natural electrical current will be formed between the zinc and rebar iron (electrons will flow from the zinc to the iron). The zinc will sacrifice, thus preserving the iron rebar (in its present state). Current will be monitored at a number of points around the tower. This system is currently used for freeway overpass columns that are experiencing similar failures. Lastly, sacrificial zinc anode bars were installed at the base of each column (bolted to the surface) as an additional measure of protection.

Similar problems were encountered at Progress Energy's Anclote Plant in Tarpon Springs, Florida. They are applying a new product called PermaTreat, formulated from reactive silicates, which penetrates deteriorating concrete, halts the corrosion of the rebar, and allegedly improves the strength and ductility of the concrete. The effectiveness of the treatment at Anclote has shown initial promise but remains to be determined over the longer term. A description of the project at Anclote is given in *Concrete Construction* magazine (2006).

Other corrosion-related problems have occurred in the condenser waterboxes and the crossover piping. On the internal components of the towers, materials substitutions have included the use of titanium straps to secure nozzles, 317L stainless for fill hangers, and stainless threaded rods to secure distribution piping cooling tower nozzles, nozzle straps, and fill hangers.

Figure C.1-2a. Repair activities of shell concrete and rebar damage

Figure C.1-2b. Removed spalled concrete on tower support columns

Figure C.1-3. Zinc mesh screen and leads

Figure C.1-4. Installation of new fiberglass and zinc on tower columns

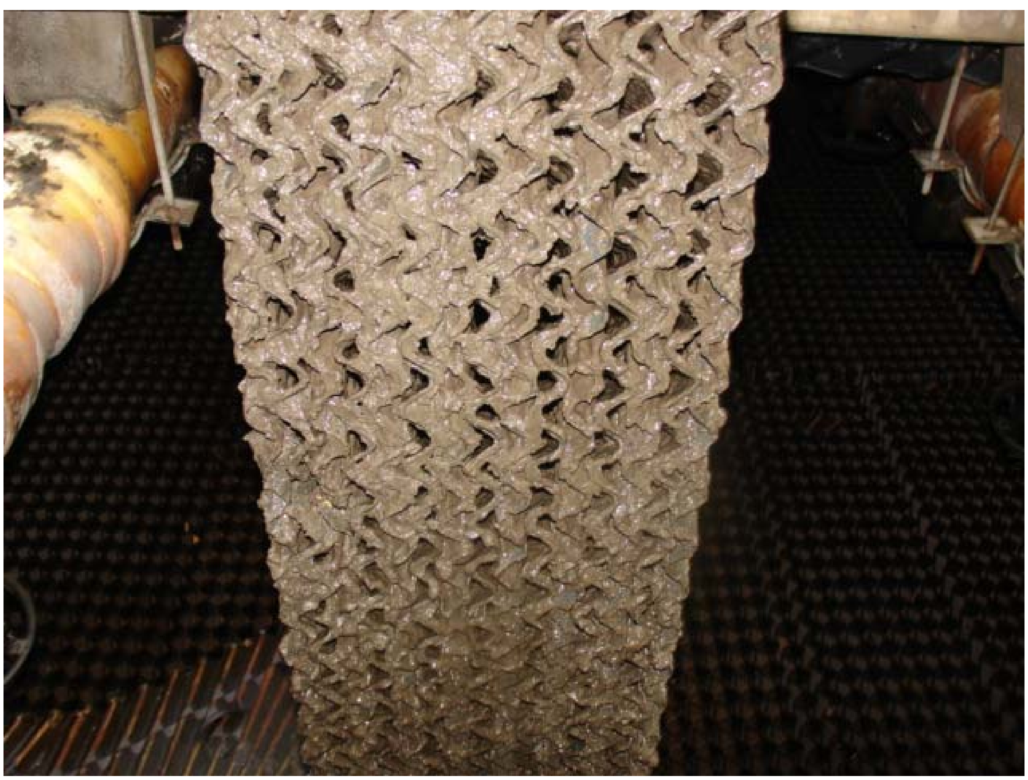
Figure C.1-5. Heavily fouled fill from tower

Additional Issues

Fill fouling and plugging

The repacking of Unit #2 with high-performance fill resulted in serious fouling and plugging. The accumulation process is initiated by the formation of biofilms to which suspended solids adhere and accumulate. Therefore, adequate chlorination to control biofouling is required. Gaseous chlorine is currently injected into the tower makeup at a rate of about 1,000 lb per 24 hours to maintain a 0.02 mgl TRO at discharge.

A modified design for chlorine injection into the distribution flumes would allow intermittent high-level chlorination on an area-by-area basis with the potential for biofilm prevention or destruction.

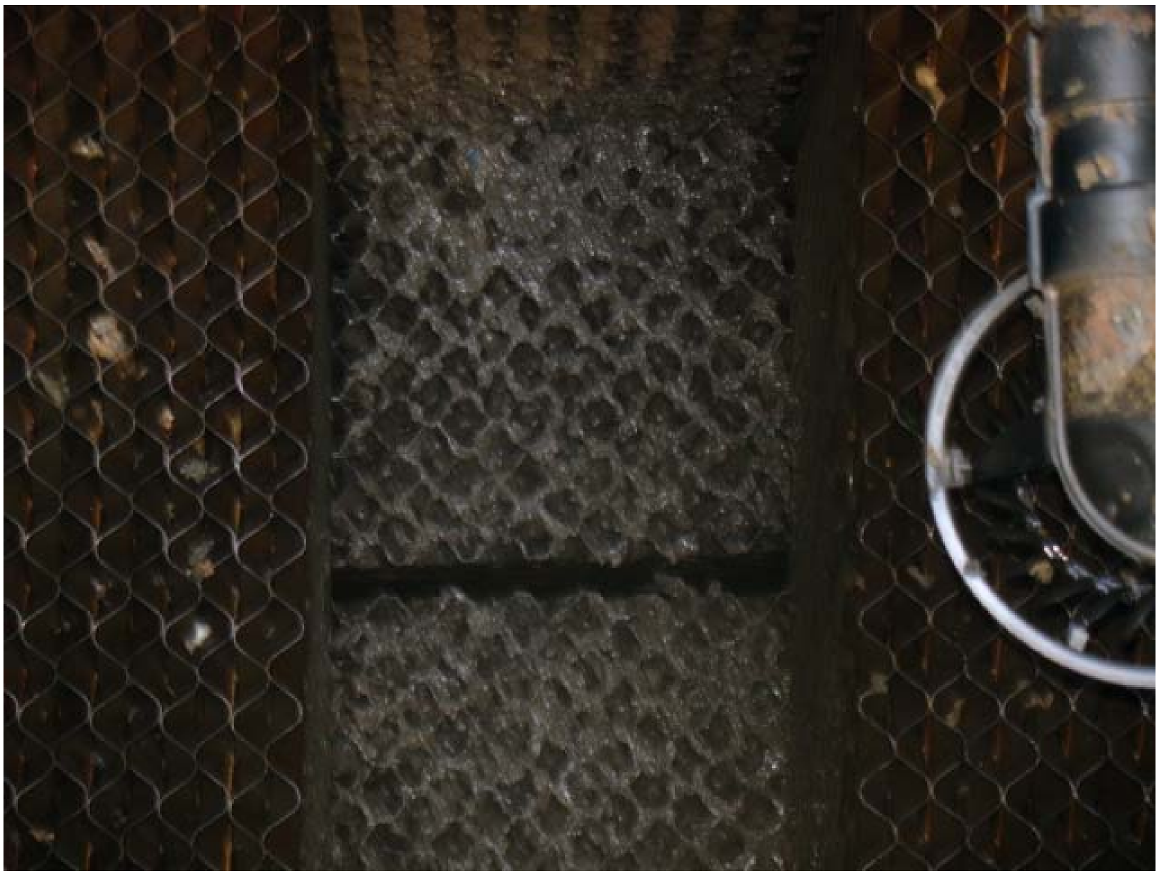

Figure C.1-6. Fouling and debris on top of fill

Sediment accumulation

Sediment accumulates in the tower basins, flumes, and headers, in addition to the towers' fill packs.

A number of design recommendations have evolved from plant experience:

- High-performance fill is not recommended to salt/brackish water towers.
- Physical features of the tower should be chosen such that sediment removal and access for cleaning is simplified, specifically:
  - Better ramp access for equipment traffic.
  - Adequate access to flumes, headers, and nozzles for cleaning and maintenance.
  - Freshwater availability at towers for washdown and cleaning during outages.
- Use of appropriate original installation materials including:
  - Chloride-resistant concrete with additives for higher density.
  - Cathodic protection to be installed during original construction.
  - Corrosion-resistant hangers, fittings, etc.

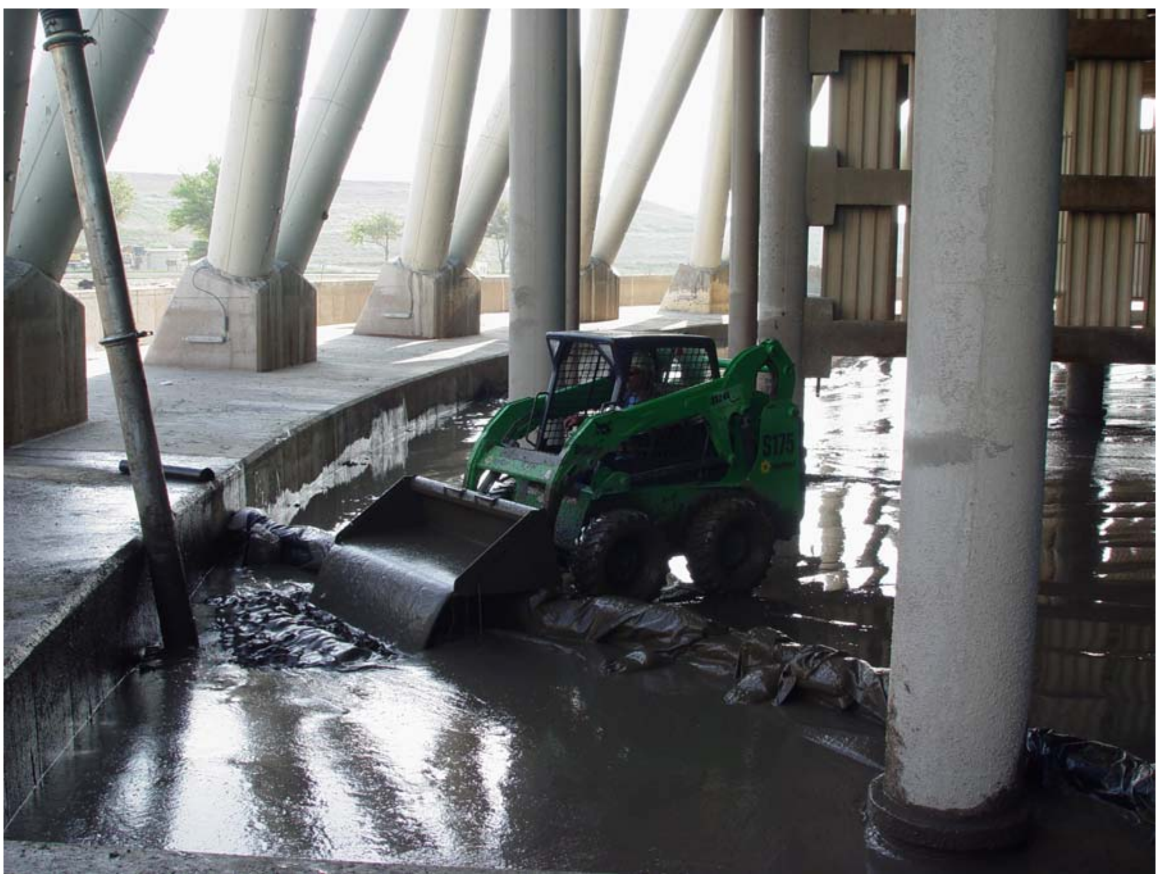

Figure C.1-7. Sediment accumulation in tower basin

Circulating water system

The original circulating water pumps were fitted with bronze impellers which suffered severe erosion in the first six months of operation. Replacement impellers of stainless steel have operated satisfactorily. Condenser waterbox and tubesheet coatings have only been fully replaced once during the life of the plant. An impressed current cathodic protection system is in place and monitored closely to ensure that damage is not occurring to the titanium condenser tubes.

C.2 Smith Electric Generating Plant

The plant was visited on the morning of March 28, 2006.

Plant Location and Contacts

Plant Lansing Smith
Gulf Power, A Southern Company
Lynn Haven, Florida, 32444-1210

George D. Fontaine, P.E. Engineer, Senior
Smith Electric Generating Plant
P.O. Box 1210
Lynn Haven, FL 32444-1210
Tel: 850-522-3479
Fax: 850-271-1697
E-mail: gdfontai@soutnernco.com

Plant Description

The plant (Figure C.2-1), owned by Southern Company's Gulf Power, consists of three units:

- Unit #1: 175 MW; coal fired; once-through cooling; on-line-mid-1960s
- Unit #2: 205 MW; coal fired; once-through cooling; on-line-mid-1960s
- Unit #3: 575 MW; 2 x 1 gas-fired combined cycle; on-line-2002
  Gas turbines: GE Frame 7; GE steam turbine

Figure C.2-1. Plant Lansing Smith

Cooling Tower

The Unit #3 cooling tower is a Marley 10-cell, back-to-back, mechanical draft counterflow tower with 200 hp, 10 meter-diameter fans. A partial picture of the tower is shown in Figure C.2-2.

Figure C.2-2. Plant Smith Unit #3 cooling tower

The design point for the Unit #3 tower is

- Circulating water flow: 125,000 gpm
- Hot water temperature: 107°F
- Cold water temperature: 86°F
- Design wet bulb: 80°F

Materials of Construction

The tower is of FRP construction with 316 stainless steel hardware. The fill is PVC low-clog fill, which has performed satisfactorily.

Source Water and Water Treatment

Tower makeup is taken from the discharge canal of the once-through cooled Units 1 and 2. The water was drawn originally from the Gulf of Mexico at full sea water salinity. The tower is operated at less than 2 cycles of concentration. Chlorine in the form of NaOCl is added daily for

1 to 2 hours for biofouling control. An anti-foaming agent is added continuously at low dose. No other chemicals such as acid for pH control, dispersants, or scale inhibitors are used.

Maintenance

The tower is in excellent clean condition with no signs of biofouling, scaling, or plugging as evidenced in Figures C.2-3 through C.2–5.

Figure C.2-3. Plant Smith Unit #3 cooling tower supports

Figure C.2-4: Plant Smith Unit #3 cooling tower bottom of fill

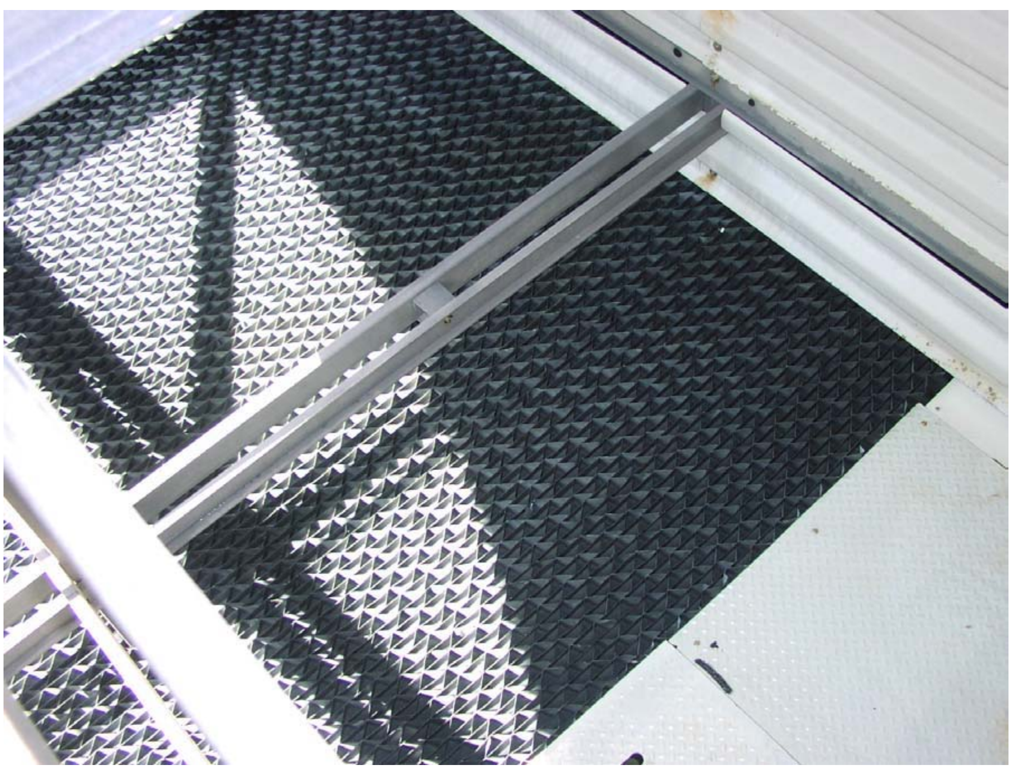

Figure C.2-5. Plant Smith Unit #3 Cooling tower top of drift eliminators

The concrete basin has some cracking and shows early signs of rebar corrosion (Figure C.2-6).

Figure C.2-6. Plant Smith Unit #3 cooling tower basin

Drift

The major problem with tower operation at the plant is corrosion of nearby surfaces caused by salt drift deposition. The drift eliminators appear to be in good condition. Although we were unable to determine what the specified drift rate had been, it is presumably in the range of 0.0005 to 0.001 % of circulating flow rate which would be typical for that age tower. This would correspond to drift rates of 0.625 to 1.25 gpm.

The primary wind direction is toward the Southwest (away from the plant) during the day but toward the plant at night. The extensive corrosion is seen in Figures C.2-7 through 2–9. Protective painting has been used but it has proven difficult to stay ahead of the problem. More elaborate alternatives including moving the tower, desalting the makeup water or converting to a fresh water makeup source have been considered but not implemented.

Figure C.2-7. Plant Smith Unit #3 drift-related corrosion

Figure C.2-8. Plant Smith Unit #3 drift-related corrosion

Figure C.2-9. Plant Smith Unit #3 drift-related corrosion

C.3 Crist Generating Plant

The plant was visited on the afternoon of March 28, 2006.

Plant Location and Contacts

Crist Generating Plant
Gulf Power, A Southern Company
One Energy Place
Pensacola, FL 32520-0340

Melvin A. (Mel) Young, III
Engineer, Senior
Tel: 850-429-2214
Fax: 850-429-2246
E-mail: mayoung@southernco.com

Arthur L. O'Mary
Team Leader—Laboratory C&R Department
Tel: 850-429-2245
Fax: 850-429-2313
E-mail: alomary@southernco.com

Plant Description

The plant, owned by Southern Company's Gulf Power, consists of 6 operating units and one retired unit.

- Unit 1—28 MW; gas-fired; once-through cooling; retired 2003.
- Unit 2—28 MW; gas-fired; once-through cooling; to be retired 2006.
- Unit 3—37 MW; gas-fired; once-through cooling; to be retired 2006.
- Unit 4—80 MW; coal-fired; once-through cooling.
- Unit 5—80 MW; coal-fired; once-through cooling.
- Unit 6—320 MW; coal-fired; mechanical draft cooling tower.
  (Unit 6 was put on-line as a once-through cooled plant in 1970; converted to closed-cycle cooling in 1973.)
- Unit 7—500 MW; coal-fired; mechanical draft cooling tower; on-line in 1973.

Figure C.3-1. Plant Crist Entrance

Unit 6 Cooling Tower

The current Unit 6 tower was built in 2005 following damage to the original tower from Hurricane Ivan in 2004. Unit 6 was retrofit with Midwest 8 cell, in-line, cross-flow tower (Figure C.3-2). The fans are 10 meter, 200 hp with 8 blades at 136 rpm.

The design point for the Unit #6 tower is:

- Circulating water flow 150,960 gpm
- Hot water temperature 115°F
- Cold water temperature 93°F
- Design wet bulb 79°F

Unit 6 Construction Materials

- Structure—wood and FRP (fiber-reinforced polymer)
- Fill—PVC (4-inch gull wing)
- Hangers and fittings—316 stainless steel
- Fan blades and stacks—FRP
- Drift eliminators—PVC

Figure C.3-2. Plant Crist Unit 6 cooling tower

Unit 7 Cooling Tower

The Unit #7 cooling tower (Figure C.3-3) was originally installed in 1973 and rebuilt in 2005 after Hurricane Ivan. It is a Marley 6615, 12 cell, in-line cross-flow tower with Marley alpha-bar fill. The 2005 rebuild retrofitted the fan deck, installed new fans and fan stacks and columns to the first lift. The fans are 10 meter, 250 hp, with 9 blades running at 136 rpm.

The design for the Unit #7 tower is:

- Circulating water flow 165,000 gpm
- Hot water temperature 121.7°F
- Cold water temperature 91°F
- Design wet bulb 79°F

Figure C.3-3. Plant Crist Unit 7 cooling tower

Materials of Construction

- Structure—wood and FRP
- Fill—PVC
- Hangers and fittings—316 stainless steel
- Fan blades and stacks—FRP
- Drift eliminators—PVC

Water Source and Treatment

Makeup water to both towers, drawn from the discharge canals of the once-through units, ranges from fresh to brackish (40 to 9,000 mgl) with a strong influence of rainfall. The towers are operated at 1.5 to 2.5 cycles of concentration at all times (lower end of range in the summer-winter months when the TDS is high).

The towers are chlorinated with 12% NaOCl for 1 to 2 hours per day for biofouling control. Blowdown is to the ash pond with a long retention time. Chlorination is discontinued when the total chlorine residual reaches 0.5 ppm. Over-chlorination is avoided to prevent corrosion in the Unit 6 90/10 CuNi condenser.

An anti-foaming agent is added continuously at low dosage and a dispersant/surfactant is added. No other chemicals such as acid for pH control or scale inhibitors are used. Corrosion rate monitors (Corrator) and MIC (microbially induced corrosion) monitors (BioGeorge®) are used.

Maintenance

Both towers appear to be clean and in excellent condition as illustrated in Figures C.3-4 through C.3-7. The basins were in good condition with no evidence of deterioration or embedded corrosion.

Figure C.3-4. Unit 6 Tower; cell 1 internal support structure

Figure C.3-5. Unit 6, 4" gull wing fill

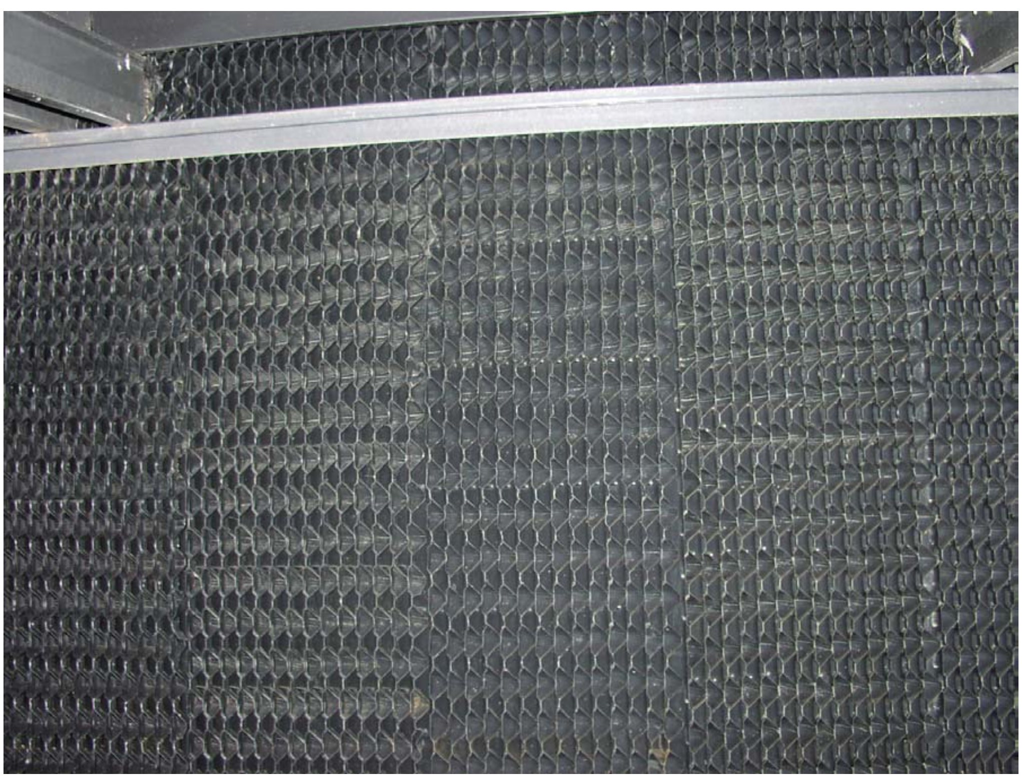

Figure C.3-6. Unit 6 drift eliminators

Figure C.3-7. Unit 6 air inlet and louvers

Drift

There was relatively little problem with drift from the towers. Some corrosion was evident on the surfaces right at the tower as seen, for example, on the riser pictured in Figure C.3-8. However, there were no reports of significant corrosion damage on other plant surfaces.

There was some switchyard arcing presumably due to salt deposition, which was controlled by occasional cleaning with freshwater sprays.

Figure C.3-8. Corrosion on riser

C.4 Watson Electric Generating Plant

The plant was visited on the afternoon of March 28, 2006.

Plant Location and Contacts

Watson Electric Generating Plant
Mississippi Power, A Southern Company
10406 Lorraine Road
P. O. Box 4079
Gulfport, MS 39502-4079

Richard A. Fairchild, P.E.
Project Manager, Environmental Projects
Tel: 228-897-6344
Fax: 228-897-6144
Cell: 228-518-0487
E-mail: rafairch@southernco.com

Patrick F. Heiter, P.E. Senior Engineer
Tel: 228-897-6109
Fax: 228-897-6302
Cell: 228-518-0487
E-mail: pfheiter@southernco.com

Plant Description

The plant, owned by Southern Company's Mississippi Power consists of five operating units:

- Unit 1: 75 MW; gas-fired; once-through cooling; on-line 1957.
- Unit 2: 75MW; gas-fired; once-through cooling; on-line 1960.
- Unit 3: 112 MW; gas-fired; once-through cooling; on-line 1962.
- Unit 4: 250 MW; coal-fired; once-through with helper tower; on-line 1968 (helper tower added in 1998).
- Unit 5: 500 MW; coal-fired; cooling tower; on-line 1973.

Figure C.4-1. Plant Watson

Cooling Towers

Unit 4 tower

The Unit 4 tower (Figure C.4-2) is a helper tower used to cool the condenser discharge and return the cold water to the discharge canal. There is no recycle of the cooling water and no cold water basin. The tower is a ceramic in-line, 10 cell, counterflow tower built in 1998. It cools a flow of 125,000 gpm through a 20°F range. The design point information (hot water temperature, wet bulb temperature) was not available.

It has recently been repaired following structural damage from Hurricane Katrina. Prior to the installation of the tower, spray modules in the cooling water canals were used (the abandoned units are also visible in Figure C.4-2).

The tower fill was originally “high performance” fill on the top 6 inches with remainder of the pack an anti-fouling fill.

Figure C.4-2. Plant Watson Unit 4 cooling tower

Unit 5 tower

The Unit 5 cooling tower (Figure C.4-3) is a Marley concrete, cross-flow, round tower (perhaps the first to be built). It was originally equipped with 13 fans to which three were later added. In addition, a small 3-cell in-line, cross-flow concrete tower was added at some later date to further augment the cooling capability (see Figure C.4-4). The current capability of the system is the cooling of 172,000 gpm through a 30°F range. Design point information was not available.

Figure C.4-3. Plant Watson Unit 5 cooling tower

Figure C.4-4. Plant Watson Unit 5's 3-cell add-on tower

Materials of Construction

Unit 4 is an FRP tower with PVC fill and drift eliminators and stainless steel fitting, hangers, and other hardware.

Unit 5 is a concrete structure with a mix of PVC, plastic coated fill grid and 316 stainless steel hardware. There are many types of fill currently in different sections of the tower.

Water Source and Treatment

The water is drawn form a lake formed by the confluence of the Biloxi and the Tchoutacabouffa Rivers. The inlet water quality ranges from fresh to brackish (70 to 12,000 mgl) with the influence of rainfall.

The cycles of concentration in Unit 5 are controlled to an LSI (Langelier Saturation Index) of 0. to 0.5. Unit 4 is a "once-through tower" with no recycle.

In Unit 5, chlorine is added as 12% NaOCl one to three days per week for biofouling control. During chlorination, the blowdown is shut off until a zero residual is reached. An anti-foaming agent is added continuously at low dosage. No other chemicals such as acid for pH control, dispersants, or scale inhibitors are used.

Maintenance

Structural damage on Unit 4 has been repaired. A number of column/beam joints which had been of the "glue and screw" type have been replaced with bolted joints (Figures C.4-5 and 4-6). No chemicals are added to Unit 4, not even chlorine, since the entire flow goes directly to discharge. As a result, plugging of the fill occurs. The approach to controlling the plugging has been to bypass the tower, allow the fill and the plugging material to dry out, and then to flush it off with the restarted water flow. Two sections of the fill are equipped with load cells to monitor the buildup of excess material.

Figure C.4-5. Unit 4 tower: "Glue and screw" joint construction

Figure C.4-6. “Glue and screw” joint construction of the Unit 4 tower

Unit 5 has had significant concrete damage over its lifetime including rebar corrosion (see Figure C.4-7). Structural bracing has been performed along with concrete patching.

Figure C.4-7. Concrete damage in Unit 5

The fill support wire grid is primarily made of plastic-coated steel wire which corrodes and breaks if the coating is damaged. The result is fill collapse as seen in Figure C.4-8.

Figure C.4-8. Fill collapse resulting from corrosion of plastic-coated steel wire

Drift

Drift eliminators in Unit 4 are relatively new and those in Unit 5 have been recently replaced. As a result there is no apparent drift related corrosion at the plant.

C.5 Pittsburg Power Plant

Notes from February 1, 2005, phone call with Ron Kosage (209-296-2528), former plant supervising chemist.

The Pittsburg plant consists of three active units—5, 6 and 7—with a generating capacity of 1,300 MW. The units were originally designed for once-through cooling. A tower was built along the cooling canal to cool a portion of the return water meet NPDES effluent thermal requirements.

The plant is located at the confluence of the Sacramento River and the San Joaquin River in Suisun Bay. Both rivers provide drainage for rainfall (and snow melt) as well as agricultural runoff to San Francisco Bay through Suisun Bay. San Francisco Bay also opens to the Pacific Ocean.

Total dissolved solids (TDS) in the summer can rise to 17,000 mg/l and will vary hourly depending on ocean tides. Total hardness (calcium and magnesium) can be very high—1,500 to 1,700 mg/l_{CaCO3} with magnesium comprising 1,000 mg/l_{CaCO3}. Colloidal organics are also high. The cooling tower is operated at 1.3 to 1.4 cycles of concentration (all year).

In the winter, when the river flow is high, TDS can range from 100 to 200 mg/l (freshwater quality) and total suspended solids (TSS) can be as high as 200 mg/l. Total hardness is 30 to 40mg/l_{CaCO3}.

The cooling tower structure is wood. The tower has plastic, high-efficiency fill, making TSS problematic. No biological control is practiced in the cooling tower. This, in combination with high TSS, can accelerate clogging of high-efficiency fill. It has been observed that some cells are not cooling, i.e., hot water is bypassing larges areas of fill (presumably because of biofouling and high TSS loading) and falling directly to the basin. No pH control or scale/corrosion control is practiced.

Ron was not sure of cooling tower hardware metallurgy. He did note that no effort was made to replace failed hardware (e.g., nuts, bolts, hangers, etc.) with like materials.

Some condensers were retubed from copper-nickel to titanium, because of under-deposit corrosion and pitting (again, presumably from high TSS in bay water).

C.6 Palo Verde Nuclear Generating Station

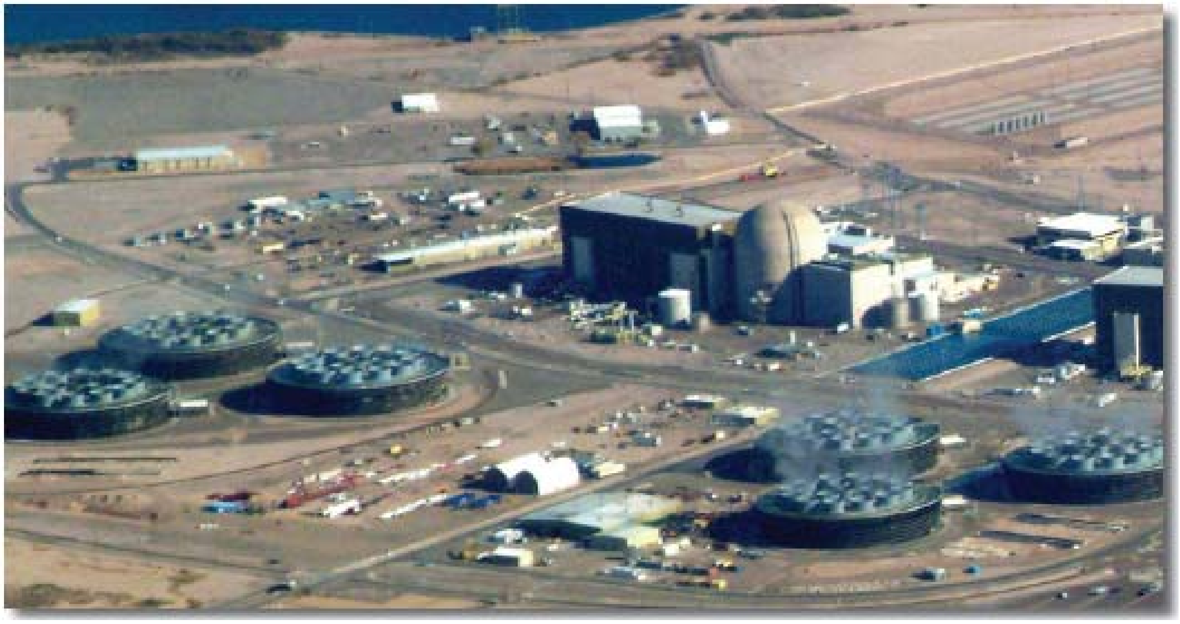

Figure C.5-6. Palo Verde Nuclear Generating Station

01/24/05, phone call, John Taylor (505-855-6258), Public Service New Mexico (part owner of PVNGC)

02/02/05, Email correspondence, Greg Lehner (623-393-2566), Arizona Public Service (operator and part owner of PVNGC)

02/02/05, phone call, Jer Chin Shih (623-393-5158), Arizona Public Service

PVNGC consists of three 1,300 MW units, which were commissioned in 1985, 1986, and 1987. Each unit has a circular, cross-flow cooling tower.

The plant receives 64,000 acre-feet[1] per year of secondary-treated municipal effluent from the City of Phoenix for cooling tower makeup (as well as other cooling needs). Water is transported to PVNGC by way of a 34.5-mile pipeline. The water from Phoenix is not filtered or chlorinated en route. Other water uses in the plant, e.g., domestic and boiler feed water, are provided by on-site water wells.

Effluent is treated at PVNGC with trickling filtration, lime softening, soda-ash softening, and final filtration. Trickling filtration uses microbiological films to reduce the concentration of organic constituents and ammonia as well as to remove suspended matter.[2]

The treated effluent generally contains less than 2 mg/l of ammonia (<0.1 mg/l after the trickling filters) and <2 mg/l of BOD (Biological Oxygen Demand). Lime soda softening and soda ash softening (two precipitation softeners in series) remove scaling constituents—i.e., hardness, alkalinity, ortho-phosphate,[3] and silica.

The cooling towers are operated (on average) at 24 cycles of concentration—at times, as high as 30 cycles. Average feedwater TDS is approximately 1,000 mg/l. Therefore, circulating water TDS is approximately 24,000 mg/l, about 70 percent of normal seawater.[4] Sulfuric acid is used to control cooling system pH to 6.9 to 7.4. The only scaling constituent of concern is $CaSO_4$ which is controlled with a common commercial scale inhibitor. TSS varies from 10 to 50 mg/l in the circulating water. Tower basins are generally cleaned during each refueling cycle (18 months).

Sodium hypochlorite is generated on-site (8 percent NaOCl) using electrolytic cells.[5]. NaCl is fed to the cells and chlorine gas (Cl_2) is generated. After it is generated it is bubbled into NaOH to form NaOCl. The cooling system is chlorinated continuously to maintain a free residual of 0.2 to 0.5 mg/l Cl_2. The cooling system is shock-fed NaOCl once per month to maintain a free residual of 5 mg/l Cl_2 for two hours. During shock feeding of NaOH, a non-oxidizing biocide is also fed at a concentration of 12 mg/l. This plan has eliminated the need to mechanically clean surfaces of biological slime.

The cooling tower structures are reinforced concrete with carbon steel (CS) rebar. There is no timber in the cooling system at all. Chloride intrusion into the concrete (by way of minute cracks) has caused rebar corrosion which creates large cracks and accelerates corrosion by exposing CS rebar to circulating water salts and oxygen. The fan decks of the cooling towers are systematically being replaced with epoxy-coated CS rebar and concrete.

Cooling tower splash fill (inverted-V type) is held in place with fiberglass hanging grids. The fill and drift eliminators are plastic. The only metal in the cooling system is the motor-gearbox-fan assemblies atop each cooling tower cell. The CS bases that hold the motor-gearbox-fan assemblies have corroded and are being ground/sanded clean and epoxy-coated to extend their life (as the fan decks are being rebuilt). Other metal in the assembly is 304 stainless steel (304SS) and it is corroding slowly and being replaced with higher grades such as 316SS. The plant has made an effort to replace small bolts with high-strength plastic or high grades of SS.

The circulating water pumps have 90-10 copper nickel impellors and the condenser tubes are titanium.

---

[1] 64,000 acre-feet per year is equivalent to 39,700 gpm.

[2] The municipal plant now nitrifies and denitrifies wastewater so ammonia levels are very low in the delivered water.

[3] Ortho-phosphate, which can form tenacious scales in cooling systems, is at relatively high levels in the treated effluent. Its concentration is significantly reduced in the lime softening step.

[4] Normal seawater, as found in the open ocean, has a TDS of 34,800 mg/l.

[5] On-site generation of NaOCl saves PVNGS 70 percent over purchasing it outright.

C.7 GEA Integrated Cooling Technologies

02/05/05, phone call, Bryan Parkin (303-987-6521)

Bryan would generally recommend the following for seawater cooling towers:

- Fiberglass structure—he would not use timber. Fiberglass intuitively has better properties, but is not time-tested. Fiberglass has only been used in cooling towers for 15 years.
- For low-TSS seawater sources, he would use high-efficiency fill. For sources subject to high TSS, he would use splash fill (inverted-V, perforated polypropylene components).
- For large metal hardware, he would use epoxy-coated carbon steel. For nuts and bolts he would use silicon bronze with plastic caps.[6] The plastic protects the relatively soft material from erosion damage. GEA has quoted duplex steel (316SS with 5%–6% molybdenum). It has excellent resistance to chloride corrosion, but is very costly. No one has used it yet because of cost.

[6] There are some products that can be sprayed onto surfaces requiring erosion protection.